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Ingrid Stuermer

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Dr. Paul C. Lauterbur
Instructor in Charge

APPROVED: Paul C. Lauterbur

HEAD OF DEPARTMENT OF CHEMISTRY

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NMR THEORY AND A STUDY OF IRON OXIDE RELAXIVITIES FOR USE IN MRI

By

Ingrid Stuermer

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Abstract

This paper explains nuclear magnetic resonance (NMR) theory and how it can be applied to magnetic resonance imaging (MRI) techniques. Relaxivities of iron oxide, a contrast agent used in MRI, are specifically studied in terms of their dependence on [Fe], temperature effects, and effects of particle size.

PRINCIPLES OF NUCLEAR MAGNETIC RESONANCE

The high degree of specificity for many biological reactions and processes depends on subtle differences in the structure and conformation of molecules. Nuclear magnetic resonance (NMR) spectroscopy is one of the few techniques available with the capacity to obtain detailed information about biomolecular phenomena. Various NMR parameters can be used to study the electronic and geometric structure of simple molecules or macromolecules, molecular motion and rate processes, and molecular interactions. A better understanding of theory is required for a satisfactory interpretation of NMR results.

Magnetic Properties of Nuclei

Roughly half of the known nuclei behave as though they were spinning like a top. The magnitude of the angular momentum

$$J' = \hbar[I(I+1)]^{1/2} \qquad \text{(Eq. 1)}$$

of this spinning motion depends on the nuclear spin quantum number I, which differs for different nuclei ($\hbar$ is Planck's constant divided by 2π). The value of the nuclear spin quantum number I is determined by the mass number and atomic number according to Table 1.

Nuclei of interest having spin 1/2 are ^{1}H, ^{13}C, ^{31}P, and ^{19}F. Nuclei of interest having spin 0 are ^{12}C, ^{16}O, and ^{32}S. ^{2}H (or D) and ^{14}N have I=1 and ^{23}Na and ^{39}K have I=3/2.

Because nuclei are positively charged (made up of protons and neutrons), a spinning nucleus gives rise to a magnetic moment

$$\vec{\mu} = \gamma\vec{J} = \gamma\hbar\vec{I} \qquad \text{(Eq. 2)}$$

where γ is the gyromagnetic (or magnetogyric) ratio and $\hat{I}$ is a dimensionless angular momentum.

Nucleus with spin I=1/2 behave as spherical entities possessing a uniform charge distribution. However, the charge distribution within a nucleus with I≥1 can be described as a prolate (cigar-shaped) or oblate (flattened) spheroid. A measure of the nonsphericity of the nuclear charge distribution is embodied in the electric quadrupole moment, which depends on I. Only nuclei with I≥1 possess an electric quadrupole moment[1]. Therefore, when a charged species (e.g. an electron) approaches a nucleus with an electric quadrupole moment, the nucleus experiences an electric field, the magnitude of which depends on the direction of approach. Possession of an electric quadrupole moment will critically affect relaxation time of a nucleus and the coupling of that nucleus' spin with spins of neighboring nuclei.

Magnetic Resonance

When a nucleus with magnetic moment μ is placed in a uniform magnetic field H_0 (oriented in the z direction), the magnetic dipole is quantized into a discrete set of orientations. This is referred to as nuclear Zeeman splitting. Each one of these orientations corresponds to a nuclear energy state or level with energy

$$E=-\mu_z H_0 \qquad \text{(Eq. 3)}$$

where μ_z $(m_I\gamma\hbar)$ is the z component of the nuclear magnetic moment. The magnetic quantum number m_I, characteristic of each nuclear energy level, depends on the nuclear spin quantum number and may take on the values

$$m_I= I, (I-1), (I-2), \ldots, -(I-2), -(I-1), -I \qquad \text{(Eq. 4)}$$

Energy levels are shown in Figure 1 for nuclei with spin quantum numbers I=1/2, 1 and 3/2. For each nuclear spin, the energy levels are equally spaced. The NMR experiment is to induce transitions between the levels by absorption or emission of a photon with the required energy. The selection rules of quantum mechanics prescribe that transitions between neighboring levels are the only allowable transitions ($\Delta m_I=\pm 1$)[2]. The energy of the photon required to induce transitions is just the energy separation between adjacent levels

$$\Delta E=\gamma\hbar H_0 \qquad \text{(Eq. 5)}$$

The Bohr condition ($\Delta E=h\nu$) permits us to give the frequency of the nuclear transition

$$\nu=\gamma H_0/2\pi \qquad \text{(Eq. 6)}$$

which is in the radio frequency (rf) portion (e.g. 100 MHz) of the electromagnetic spectrum. Therefore, for any particular nucleus in a given magnetic field, the NMR frequency will be characteristic, depending primarily on the gyromagnetic ratio peculiar to that particular nucleus.

The theory of electromagnetic radiation states that the probability of a photon inducing a transition from a higher energy level to a lower one is the same as the probability for an induced transition from a lower to a higher energy level. Therefore, in a large ensemble of spins, a net absorption or emission depends only on the difference between the number of nuclei in the upper and lower energy levels.

The distribution of nuclei in the various possible energy states is given, under conditions of thermal equilibrium, by the Boltzmann equation

$$N_{upper}/N_{lower}=e^{-\Delta E/kT}=e^{-h\nu/kT} \qquad \text{(Eq. 7)}$$

where N_{upper} and N_{lower} represent the population (i.e. number) of nuclei in upper and lower energy states, respectively. With radiofrequencies used in NMR, the population ratio might typically be 1.000035 (at ν=220 MHz) for hydrogen nuclei in thermal equilibrium at room temperature. That means for every 1,000,000 nuclei in the upper energy state there are 1,000,035 nuclei in the lower energy state. Without this small excess in the lower energy state, there could be no nuclear magnetic resonance phenomenon.

NMR Relaxation

A nuclear spin system in a stationary magnetic field H_0 may be considered. At equilibrium, the spin populations of the various Zeeman energy levels will be described by the Boltzmann distribution (Eq. 7), giving the lower energy levels a slightly greater spin population, as just discussed. If a radiofrequency field at the resonance frequency is applied to the system, the probability of an upward transition is equal to the probability of a downward transition. Because there is a greater spin population in the lower energy leverls, there will be more upward transitions than downward transitions, resulting in a nonequilibrium spin distribution. If this process continues, the excess of nuclei in the lower energy state will continually diminish with consequent decrease in the NMR signal intensity. Under certain circumstances, the two spin populations may be equal and the NMR signal may disappear completely. This phenomenon is referred to as saturation and, in practice, can occur if strong rf fields are applied. For an NMR signal to persist, some mechanism must be available for replenishing the number of nuclei in the lower energy states.

There are various mechanisms leading to radiationless transitions that cause the perturbed system to return to the equilibrium spin distribution. These radiationless transitions are called relaxation processes. There are two kind of relaxation processes: spin-lattice (or longitudinal) relaxation and spin-spin (or transverse) relaxation[3]. The spin-lattice relaxation time is designated by T_1 and the spin-spin relaxation time is designated by T_2. T_1 is a characteristic time describing the rate at which the nonequilibrium spin distribution $(N_{lower} - N_{upper})$ exponentially approaches equilibrium $(N_{lower} - N_{upper})_{equil}$ following absorption of rf energy.

$$(N_{lower} - N_{upper}) = (N_{lower} - N_{upper})_{equil}\,(1 - e^{-t/T_1}) \qquad \text{(Eq. 8)}$$

The lattice is the environment surrounding the nucleus - the remainder of that molecule as well as other solute and solvent molecules. Spin-lattice relaxation occurs by interaction of the nuclear spin dipole with random, fluctuating magnetic fields caused by the motion of surrounding dipoles in the lattice that happen to have components fluctuating with the same frequency as the resonance frequency described in Eq. 6. The energy of the radiationless transition is transferred to the various energy components of the lattice as additional rotational, translational, or vibrational energy (with total energy unchanged) until the nuclear spin system and the lattice are in thermal equilibrium. In solids or viscous liquids, the T_1 relaxation may be several hours. In most nonviscous liquids or solutions, T_1 is usually on the order of 0.001-100 sec.

Spin-spin relaxation processes also have a relaxation time, T_2, which characterizes the rate of these relaxation processes. The sources of the random magnetic fields giving rise to T_1 relaxation will also lead to T_2 relaxation. However, spin-spin relaxation has other relaxation mechanisms that may contribute to T_2. Simply, the additional contribution to spin-spin (or transverse) relaxation is the result of chemical exchange or mutual exchange of spin states by two nuclei in close proximity. The distribution of energy among the spins in this manner is an adiabatic process and, although it decreases the lifetime for any particular nucleus in the higher energy state, it does not change the number of nuclei in the higher energy state.

There are basically two ways of looking at the NMR phenomenon. The first was the basis for the previous discussion - essentially a quantum mechanical description of discrete nuclear energy levels, the nuclear populations of which can be described by the Boltzmann distribution (Eq. 7). Another way of viewing the nuclear magnetic resonance phenomenon is to consider it as a forced precession of the nuclear magnetization in the stationary magnetic field H_0 which is perturbed by application of radiofrequency field H_1. This classical approach is largely owing to Felix Bloch and describes NMR experiments quite accurately, especially for liquid samples.

Classical Description - Bloch Equations

Early in the history of NMR, Bloch[4] provided a classical description of the NMR experiment, deriving a set of very useful equations describing a group of nuclei in a magnetic field simply from phenomenological considerations. The rationale of the approach is now presented.

To simplify matters, all magnetic nuclei in a system will be assumed to be identical and to have spin I=1/2. According to the classical theory of electromagnetism, a magnetic moment $\vec{\mu}$ in a field $\vec{H}_0$ will experience a torque

$$\vec{T} = \vec{\mu} \times \vec{H}_0 = d\vec{J}/dt \qquad \text{(Eq. 9)}$$

where $\vec{J}$ is the angular momentum. Because $\vec{\mu}=\gamma\vec{J}$, the motion of the magnetic moment is given by

$$d\vec{\mu}/dt = \gamma\vec{\mu} \times \vec{H}_0 \qquad \text{(Eq. 10)}$$

which describes the precession of the nuclear magnetic moment about the z axis. The z axis is defined as the direction of the H_0 field. This precession causes $\vec{\mu}$ to generate a cone about the z axis, as shown in Figure 2. The frequency of the precessional motion

$$\nu_0 = \gamma H_0/2\pi \qquad \text{(Eq. 11)}$$

is called the Larmour frequency; it is, in fact, the NMR frequency for that nucleus as will be seen. The Larmour angular frequency is

$$\omega_0 = 2\pi\nu_0 \qquad \text{(Eq. 12)}$$

We now consider the application of a small rf field $\vec{H}_1$ rotating in the plane perpendicular to $\vec{H}_0$ with the angular frequency ω as shown in Figure 2. The $\vec{H}_1$ field will produce a torque as in Eq. 9 on the moment $\vec{\mu}$, tending to tilt $\vec{\mu}$ toward the plane perpendicular to $\vec{H}_0$. If $\omega \neq \omega_0$, only a small periodic perturbation will be exerted on $\vec{\mu}$ as $\vec{H}_1$ quickly loses step with $\vec{\mu}$. This results in a small precessing motion of $\vec{\mu}$ about the original $\vec{\mu}$ direction as shown in Figure 2. As ω approaches ω_0, the torque from the $\vec{H}_1$ field tilting $\vec{\mu}$ toward the plane perpendicular to $\vec{H}_0$ will be exerted for a longer time. This will give a larger amplitude of precession. At $\omega=\omega_0$, the effect of the torque will be the greatest and the amplitude of the precession will be the largest. In this process, energy is provided to the spin at the expense of the rf field. If the frequency ω of the rotation of $\vec{H}_1$ is varied through the Larmour frequency, energy is absorbed by the spin system and the magnetic resonance phenomenon is observed. In practice an oscillating rf field is used. However, the oscillating field can be broken into two components rotating with equal angular velocities in opposite directions.

Only the component rotating in the same direction as the precession of the moment will affect the moment.

In this section, the properties of those nuclei of interest for NMR were discussed, namely, those possessing an angular momentum $\vec{J}$ and a magnetic moment $\vec{\mu}$. In practice, a large number of nuclei are observed rather than a single nucleus. This ensemble can be treated on a macroscopic scale.

The macroscopic nuclear magnetization

$$\vec{\mu}=(M_x, M_y, M_z) \qquad \text{(Eq. 13)}$$

of a sample is defined and the magnetic moment per unit volume. In the absence of an H_1 field at the resonance condition, the x and y components of the individual spins are randomly oriented in the xy plane such that $M_x+M_y=0$. Consequently, the macroscopic magnetization is the sum of the z components of the individual nuclear spins

$$\vec{\mu}= M_z\vec{k} = (\Sigma\, \mu_z)\vec{k} \qquad \text{(Eq. 14)}$$

where the z axis is defined by the direction of the stationary field $\vec{H}_0$ and the summation is over a unit volume of the sample ($\vec{k}$ is a unit vector oriented along the z axis). For spin I=1/2 nuclei, the individual moments will align themselves, as shown in Figure 3, such that their z components will be either parallel or antiparallel to the direction of $\vec{H}_0$, corresponding to two energy states. An $\vec{M}$ exists because there is a greater number of spins in one state (parallel to $\vec{H}_0$), as described by the Boltzmann distribution.

The equation of motion for the macroscopic magnetization in a homogenous field may be written as

$$d\vec{M}/dt = \gamma(\vec{M} \times \vec{H}) \qquad \text{(Eq. 15)}$$

because the macroscopic moment is obtained as the sum of the individual moments. $\vec{H}$ is composed of $\vec{H}_0$ and $\vec{H}_1$.

Equation 15 describes the precession in the $\vec{H}_0$ field and the absorption of energy by the application of $\vec{H}_1$. However, it does not account for the relaxation processes that tend to redistribute the energy absorbed by the system of spins. In a stationary field, $H_0 = H_z$, the z component of $\vec{M}$, M_z, will try to take on its equilibrium value M_0. Analogously to Eq. 8, the relaxation of M_z back to its equilibrium value following absorption of rf energy can generally be described by an exponential decay

$$dM_z/dt = -(M_z - M_0)/T_1 \qquad \text{(Eq. 16)}$$

where T_1 is the spin-lattice relaxation time[5]. T_1 is often referred to as the longitudinal relaxation time, being the relaxation of the component of $\vec{M}$ in the $\vec{H}_0$ direction.

Absorption of rf energy can also give rise to x and y components of $\vec{M}$. These components will rotate about the z axis at the Larmour frequency. However, because of fluctuations and slight differences in local magnetic fields, the transverse components of the individual nuclear spins will get out of phase. Because M_x and M_y are sums of the individual nuclei's x and y components, M_x and M_y will decay to zero. This decay may be described by

$$dM_x/dt = -M_x/T_2 \qquad \text{(Eq. 17)}$$

and

$$dM_y/dt = -M_y/T_2 \qquad \text{(Eq. 18)}$$

where T_2 is the transverse relaxation time[6]. As noted in the last section, T_2 is also called the spin-spin relaxation time and may be defined as the time constant for exponential decay to zero of the magnetizatin in the xy plane. For the following discussion, inhomogeneities in the magnetic field of the labor magnet will be considered neglible, so the decay constant will be a true T_2. The decay constant will be smaller if the magnetic field is not completely homogeneous, and the decay constant caused by magnetic field inhomogeneity will be designated T_2^*[7].

Combining the relaxation process with the motions produced by torque, we have the Bloch-equation:

$$d\vec{M}/dt = \gamma(\vec{M} \times \vec{H}_0) + \gamma(\vec{M} \times \vec{H}_1) - (\vec{i}M_x + \vec{j}M_y)/T_2 - \vec{k}(M_z - M_0)/T_1 \qquad \text{(Eq. 19)}$$

where $\vec{i}$, $\vec{j}$, and $\vec{k}$ are unit vectors in the laboratory (x, y, z) cooridnate system.

NUCLEAR MAGNETIC RESONANCE IMAGING

Although today radioisotope tests are synonymous with imaging, the original application of radioisotope studies was in the sphere of functional measurement. One of the earliest techniques for measuring in vivo metabolism was the use of radioiodine to study the function of the thyroid gland[8]. More recently alternative noninvasive methods for studying human physiology have become available including CT, digital subtraction imaging, ultrasound, and now nuclear magnetic resonance.

The aspects of physiology and tissue analysis can be divided into three groups - blood flow, metabolism and tissue characterization. Tissue characterization is of main concern in this paper.

Attempts to differentiate tissue on morphological grounds have always proved difficult. This is not surprising when often the diagnosis becomes obvious only when tissues are fixed, sectioned and examined under a microscope. Many lesions can provide similar morphological appearance on microscopic examination.

NMR tissue characterization in principle has several advantages over techniques such as radionuclide technique and ultrasound. Unlike techniques based upon anatomical parameters, the measurements carried out by NMR are related to the chemistry of the tissues under examination. Essentially three parameters are measured: the density of protons, longitudinal and transverse relaxation times. Altering the pulse sequences can produce different weightings of the relaxation times and, in theory at least, the fact that three parameters are being used instead of one should increase the chances of this being more disease- or tissue-specific than others. However, there are also theoretical disadvantages associated with NMR tissue characterization. These include the fact that since one is measuring signals from protons and their binding in molecules, the technique is more sensitive to fluid, oedema and fat rather than to specific tissues. However, NMR does have a higher sensitivity and specificity than other techniques.

Tissue Characterization By NMR

Nuclear magnetic resonance has been used in the examination of tissues almost since the discovery of the phenomenon by Bloch and independently by Purcell[9] in 1946. In vitro tissue studies were occasionally reported during the 1950s and 1960s, e.g. Odeblad et al.[10], Bralton et al.[11]. It was, however, the report of Damadian[12] and his co-workers in the early 1970s, describing differences in proton relaxation times between normal and pathological tissues, which initiated interest in the application of NMR to biological and medical studies. It was not until 1973 that Lauterbur[13] was the first to actually apply NMR to imaging. These studies have culminated in the widespread use of NMR spectroscopy and especially of imaging used today. NMR is applicable to the study of a large number of nuclei. The great majority of biological studies have, however, concentrated on the hydrogen nucleus, or proton.

The nature of tissue and the methods used in biological NMR studies, both in vitro and in vivo, limit the chemical range of protons which contribute to the NMR signal. Protons attached to large molecules or to rigid or semi-rigid structures such as membranes do not contribute to the signal. In these cases the protons are very highly constrained and the T_2 relaxation time is extremely short. They are effectively invisible in normal tissue studies. If, however, the protons are part of rapidly-moving small molecules they maintain phase coherence after a 90^{O} rf pulse for a much longer time and energy loss by spin-lattice interactions is also much slower. Hence, the protons of molecules such as water have T_1 and T_2 relaxation times in the measurable range. Apart from water, the only other protons which contribute significantly to tissue NMR signals are those of fat, i.e. triglycerides. In this case the long fatty acid $-CH_2$ chains have considerable mobility (unlike the chains of membrane lipids) and the rate of dipole and other interactions is reduced[14]. Hence T_1 and T_2 are increased sufficiently to be measured.

These limitations of parameters define the set of properties upon which one must base attempts to achieve tissue characterizations in proton NMR studies. We can only observe water and triglycerides. Only the standard parameters, i.e. total NMR signal size (related to proton or spin density which is usually symbolized by the letters PD or the Greek letter ρ), the spin-lattice (T_1) and spin-spin (T_2) relaxation times and in certain experiments a small range of other properties including flow, diffusion and chemical shift.

NMR PARAMETERS

The precise value for each of the NMR parameters in a particular sample is determined by the local environment experienced by the detectable protons in that sample. For most body tissues, water protons are the major contributors to the NMR signal. Therefore, water will be used to illustrate the ways in which the values of the NMR parameters can be varied.

Proton Density and Signal Size

The NMR signal size is a difficult quantity to measure in absolute terms even in a small sample in an NMR spectrometer and it becomes extremely difficult to quantify in the NMR image. The signal size is related to the net magnetization of the sample, as already discussed.

Temperature and applied magnetic field strength are fundamental factors affecting NMR signal size but there are many other factors, mainly instrumental which also have an effect. In an ideal NMR experiment, the signal would be measured as the free induction signal amplitude after delivering a perfect and infinitely short 90° rf pulse to a sample which had never previously experienced such a pulse, i.e., the sample was totally relaxed. In a real experiment, however, the 90° pulse is of finite duration, hence allowing some relaxation to take place during its delivery. Any imperfections, i.e. a larger or smaller pulse affecting the angle of the magnetization, will affect signal size. In addition the sample is usually subjected to a series of pulse sequences which at best are separated by fairly long inter-pulse intervals (t_r). If t_r is five times the T_1 relaxation time of the protons then the signal will be reduced to 99.3% of its theoretical maximum with further reducitons in t_r causing proportionate diminution of the signal[15].

Proton density alone yields a very low contrast NMR image, which is mainly a reflection of the small variation in water content between most body tissues.

T_1 and T_2 Relaxation Times

Tissue water does not exhibit the same relaxation characteristics as pure free water. If a sample of pure water is examined, we find that T_1=T_2= approximately 3s and that this value is frequency independent. In tissue, T_1 is considerably longer than T_2 and both of these are much shorter than the pure water values. T_1 also shows a marked frequency dependence. The differences in relaxation characteristics arise from constraints on the movement of water molecules in tissue due to the presence of other constituents such as macromolecules, membranes, etc., which have varying hydrophobic and hydrophilic qualities affecting the extent to which the water molecules are bound.

A further complication in the measurement of tissue relaxation times is introduced by the fact that the necessary sample is of large size both for in vitro studies (generally in the order of 0.2-0.5g) and in vivo where the sample is the contents of one image voxel. Hence, we are not looking at water in a single cell or even, necessarily of a single cell type. The measured value is therefore an average of all the T_1 or T_2 values from all the different environments inside and between the various cells and cell types which constitute the sample. Despite this apparent complexity of origin of the signal we find that in the majority of tissues, the T_1 relaxation curve is of the simple, single exponential type that we would expect from the water protons in a protein solution. T_2 relaxation shows a greater tendency towards multi-exponentiality, suggesting that T_2 is a more sensitive indication of the complexity of the cellular environment[16].

Measurement Method

Measurement of T_1 of tissue in vitro is most simply and most accurately performed by use of a simple inversion recovery sequence. In this case a 180° rf pulse is delivered to the sample to invert the spin population. A short period, *t*, is allowed for relaxation (spin-lattice or longitudinal relaxation only after a 180° pulse) and the sample is then subjected to a 90° rf pulse which puts the magnetization into the xy plane in which it is measurable as the size of the free induction signal. By varying the duration of *t*, one can obtain a plot of signal size against *t*. In a simple sample this plot will be a single exponential whose time constant is T_1.

T_2 needs a more complex method of measurement and is normally obtained using some form of spin echo pulse sequence, e.g. the Carr-Purcell-Meiboom-Gill (CPMG) sequence[17]. In this case a train of spin echoes is produced and the size of the echo is plotted against time after the initial 90° rf pulse. Again in a simple system this will yield a graph of single exponential form whose time constant is T_2. However, in this paper, only experiments with T_1 are considered.

It is seen, therefore, that normal in vitro experimental methods provide a decay curve with as many points on it as the experimenter chooses to obtain. From this a single value for the time constant can be obtained. In NMR imaging, however, calculated T_1 and T_2 values are often taken from very few points on the relaxation curve, making it very difficult or impossible to analyze for multi-exponentiality. Most relaxation time values quoted from NMR imaging must, therefore, be regarded simplistic rather than accurate.

Pharmaceuticals for Functional Studies

Magnetic resonance imaging (MRI) has advanced technically to the point where it is already regarded by many radiologists as the preferred imaging method for most studies of the brain. However, there is less than uniform opinion concerning the potential of MRI in a number of other important clinical areas, such as in studies of the abdomen, where there is poor tissue contrast.

It has been suggested that this and other limitations of the MRI method may be minimized by the use of image contrast agents. These are exogenous chemicals administered to the patient which, by influencing the magnetic resonance properties of the water in the region of the pathology, serve to heighten the contrast between that tissue and its surroundings.

The characteristic properties of an ideal contrast agent for MRI are obvious. Fundamentally, it should be non-toxic and provide effective contrast when used in very small quantities. In turn, these characteristics imply that it should have an appropriate balance of pharmaceutical properties such as tissue uptake and excretion rate; ideally, the material should be organ specific and, even more so, be specific to just one particular pathology.

Most MR images are displayed on a grey scale with white implying the highest effective intensity and black the lowest. This effective intensity (EI)=concentration=My, where the concentration is of the magnetic nuclides in the tissue and My is the amount of their magnetization present at the actual time of the MR measurement. Although there is intrinsic variation of water concentration between different tissues, it is the substantial tissue dependence of My which provides the major source of image intensity variations and hence image contrast. This relationship stems from the fact that each magnetic nucleus has two characteristic relaxation times, T_1 and T_2, which govern the rate at which the magnetization of that nuclear species can be accurately measured. The effects of T_1 values will be emphasized here. Consider then, an MR imaging protocol in which the magnetization is measured repeatedly at a predetermined rate. Tissues which have a short T_1 value will recover all their My between successive scans and hence their perceived intensity in the final image will accurately reflect their water content; that intensity will be high and hence the tissue will show, for example, white. On the other hand, tissues with T_1 values which are long compared with the experimental repeat time will progressively lose magnetization and will show as a darker color on the image intensity grey scale.

It is this variation of endogenous tissue relaxation characteristics which provides the wealth of image contrast which makes MRI such a powerful diagnostic procedure. These agents are chosen because they can alter the relaxation times of protons in those tissues with which they are in contact. Thus, if an agent which can shorten the T_1 values is introduced into a particular organ, then the perceived intensity of that particular region of the final image can be enhanced by choice of suitable imaging times. Obviously, the greater the specificity with which an agent can be delivered to a specific tissue, the greater will be the induced contrast.

In this experiment, relaxation times for iron oxide (specifically, magnetite) are characterized. Magnetite[18,19] is being considered as a contrast agent because of its ferromagnetic properties, it does not introduce any substances which are not already present in the body (iron is found in blood), and it also remains in the body for a longer period of time than other contrast agents. Here, with the use of a relaxometer which measure T_1 values specifically, we are able to establish relaxivities of iron oxide for future MRI use.

RELAXOMETER THEORY[20]

The relaxometer used is field cycling. This means that the magnetic field cycles through three values during T_1 measurements (H_{SH}= soaking field, H_R =resonant field, and H_M=field at which T_1 is to be measured). The method used is also referred to as wide-line spin-echo which means the magnetization is detected by a spin echo which results after a 90°-τ-180° pulse sequence in a low resolution (wide-line) process as seen in Figure 4.

At H_{SH}, the sample is soaked so that the sample reaches equilibrium at the magnetization M_0. The field then switches to H_M and then falls with a rate of T_1. The relaxometer remains at H_M for varying times t_M and then switches to H_R where the pulse sequence begins. The area of the spin echo is proportional to the magnetization M_{t_M} which corresponds to a single point on the exponential decay. This process is repeated for varying t_M between 0 and about $1.5T_1$. Infinity times ($t_M \geq 5T_1$) are also measured to determine M_∞. An average M_∞ is subtracted from M_{t_M} and T_1 is then determined from an exponential fit to values of M_{t_M}-$M_{\infty_{avg}}$ at the specific H_M.

This cycle is repeated for different H_M varying from 0.01MHz to 50MHz to obtain relaxivity curves at specific temperatures. The relaxometer contains an electromagnet. This field strength is controlled via a computer by varying current. The temperature is controlled by a refrigeration/heating system which is directly connected to the sample chamber.

SAMPLE PREPARATION AND RESULTS

All the iron oxide samples were commercially bought. These concentrated samples were either made into solution with distilled water or prepared with an agar gel.

The same procedure was used to make all the water solutions. All commercial samples had known concentrations. Before transferring material, the contents in the sample bottles were shaken vigorously to ensure uniform distribution of iron oxide particles. After being well shaken, a calculated volume of concentrated sample was pipetted into a 5 or 10 ml volumtric flask in order to get a desired concentration. The sample was then diluted to volume with distilled water. After shaking the new solution of concentration, approximately 0.6 ml of the solution were pipetted into a relaxometer sample test tube. The tube was then stoppered, given a sample number (which included a description of the solution), and then ready to be measured by the relaxometer. Water samples were prepared just before being run and then discarded after being tested.

It was observed that some of the iron oxide sample particles settled to the bottom of the sample test tube rather quickly (less than 30 minutes). This would affect relaxometer measurements since the particles would not be uniformily distributed during the relaxometer running time. This being the case, agar samples were prepared for some samples in order to suspend the iron oxide particles for extended periods of time (on the order of weeks).

All agar samples were prepared in the same manner. Initially, 0.5% (weight of agar powder per volume of solution) of agar powder was dissolved in hot distilled water. Small calculated amounts of pre-shaken concentrated iron oxide samples were added to a relaxometer sample test tube (total volume approximately 0.6ml). This mixture was dispersed by ultrasonication. The sample was then quickly cooled by putting the test tubes in a water/ice bath. This prevented the particles from settling down. The sample was then stoppered and ready to be put into the relaxometer. It might also be noted that the agar samples remain gelled below 50°C. For our purposes, a temperature range of 5°C - 37°C was used. No considerations for a melted agar sample had to be taken into account. Agar samples were prepared once and kept refrigerated when not being used in the relaxometer.

Relaxation times of both pure distilled water and 0.5% agar gel were taken at frequencies ranging from 0.01MHz to 50MHz. The data from these two runs were subtracted from the data of the actual samples to be studied in order to obtain relaxivities of only the material of interest, which in this case is iron oxide.

Data for the different samples were obtained at varying temperatures within the above described frequency range. The data tables indicate the material used, a lot number (from the manufacturer), a description of the material, the temperature at which the sample was run, and the concentration of iron [Fe] in the sample. The tables also show a listing of the frequencies measured (MHz), the corresponding field strength (Gauss), the rate of $1/T_1$ (1/seconds), the rate of the sample minus its background (water or agar gel), and the relaxivity (1/(seconds*mM). The relaxation times of the respective background materials themselves are also listed on each data sheet.

The relaxivities obtained where then plotted relaxivity (1/s*mM Fe) vs. frequency (MHz) to normalize the graphs for easier analysis. All graphs and data tables are found at the end of this paper.

INTERPRETATION OF DATA

Iron oxide, specifically magnetite (Fe_3O_4), is currently being studied for use as a contrast agent in NMR imaging. A contrast agent, as the name implies, helps distinguish between different types and/or states of tissue (sick or normal). In this study, we are looking at the relaxivities of iron oxide to see how they are affected by concentration, temperature, and particle size.

Dependence on [Fe]

When studying the dependence of relaxivities on [Fe], data with varying [Fe]'s are compared while temperature and particle size remain constant. By definition, relaxivity is

$$R_1 = (1/T_1 - 1/T_{1(\text{background})})/[Fe] \qquad \text{(Eq. 20)}$$

R_1 should be constant with different [Fe]'s , since there exists a linear relationship between the two.

Looking at the A samples run at 20°C with [Fe]=0.19mM, 0.13mM, and 0.065mM, the relaxivities at 0.19mM and 0.13mM are almost exact (Graphs and Data Sheets A120A and A220A). The data for [Fe]=0.065mM (Graph A320A) differs from the two higher concentrations by at most 28%, but this difference is for the most part uniform throughout the frequency range measured. Looking at Graph A320A, the curve is not as smooth as the other two. This would make one assume that there must have been extra noise when running this sample. One explanation for this would be that [Fe] for A320A was too low.

Comparing B samples at 20°C, the curves are the same shape, but the relaxivities are slightly off (at most 15% difference). This can be seen by comparing Graphs B220 and B520. At 37°C two more samples were run the same tenfold difference in concentration as the 20°C samples. Comparing Graphs B237 and B537, it is easily seen that the relaxivities are the same. This also supports the statement that there is a linear dependence of [Fe] on R_1.

The C samples are also compared with a tenfold difference in [Fe]. At 20°C, the relaxivity curves (Graphs C220 and C520) are identical as is the data for the samples run at 37°C (Graphs C237 and C537) (allow 5% error at end points).

L samples were also run at 20°C with a threefold difference in concentration. Comparing Graphs L420 and L520, the relaxivities are exact with respective frequencies.

Comparing these four sets of data where the samples varied from A (superparamagnetic particles in a polymeric matrix) to B, C, and L (magnetite coated particles), all four groups showed a linear relationship between R_1 and [Fe]. By normalizing the graphs, this dependence is easily seen. This data supports the original assumption that these iron oxide particles have relaxivities that behave according to the linear relationship to [Fe].

Temperature Effects

Different iron oxide samples were also run at equal [Fe]'s but with varying temperatures.

Looking at graphs A220A and A237A, the relaxivity curve for 37°C is approximately 20% lower than at 20°C. Although the shape of the curve is the same for both, the peak heights vary slightly. Looking carefully at Data sheets A220A and A237A, it is observed that the peak height for the higher temperature is at a slightly higher frequency.

Comparing Graphs B205, B213, B220, and B237 which all have [Fe]=0.13mM ranging from T=5°C to T=37°C, it is seen that the higher the temperature, the lower the relaxivity. The same effect is seen with Graphs B520 and B537, though not as great. For these second two plots the difference in [Fe] was tenfold less which probably accounted for the smaller difference in relaxivities at the different temperatures.

For Graphs C220, C237 and C520, C537, the same effect is also seen as with the B samples. However, the effect is greater at frequencies less than 1MHz.

When comparing Graphs D220 and D237, the curve shapes differ slightly at the lower frequencies. For the most part, the relaxivities are lower at the higher temperature. Here it is also noted that the peak of the curve shifts to a higher frequency at a higher temperature, as it did for the A samples.

The L samples (Graphs L405, L410, L415, L420, L425, L430, L435) are an excellent example showing the gradual decrease in relaxivity over a temperature range of T=5° to T=35°C with increments of 5°C. Comparing the two extreme temperatures, relaxivity decreases by approximately 16%. However, it should be noted the shape of the curve is not linearly dependent with increasing temperature.

Two phenomena are observed from these data. Temperature affects magnitude and peak position of relaxivities.

The magnitude difference is explained by the fact that an increase in temperature increases the diffusion coefficient. Therefore, the average time the water molecules spend near the particles is smaller and the particles effect on their relaxivities is smaller. In other words, the more time the water molecules spend near the particles, the greater the relaxivity of the particle.

The position of the peak is also altered due to diffusion effects. As the temperature increases, the diffusion coefficient increases, as just mentioned. The longitudinal relaxation times can be viewed as a spectral density function (Fig. 5). This function has an inflection point which directly relates to curve peaks. The constant

$$t_R = R^2/D \qquad \text{(Eq. 21)}$$

where R is the radius of the particle and D is the difffusion coefficient, is part of the spectral density function. As the temperature increases, the diffusion coefficient increases, the constant t_R decreases, which causes the inflection point on the function to move to a higher frequency, which causes the peak of the relaxivity curves to move to a higher frequency.

Effects of Particle Size

Comparing three different samples of varying particle core diameters at constant temperature, one can see a definite distinction between them.

The Polysciences samples 19631 to 19633 (Graphs of C, B, and L, respectively) are magnetite coated particles of varying particle core sizes. This means the sample has a magnetite core coated with polystyrene (a nonmagnetic polymer which does not affect relaxivities). A schematic diagram would look like Figure 6. The exact diameters are not known, but it is a fact that their core size increases with increasing Polysciences sample number. Comparing Graphs C520, B220, and L420, it is obvious that the relaxivities increase respectively with increasing core diameter. This implies that the larger the particle, the stronger the magnetic effect.

This can easily be explained by knowing that the core diameter directly effects μ (magnetic moment).

$$\mu^2=\gamma^2\hbar^2S(S+1) \qquad \text{(Eq. 22)}$$

where S equals spin. However, relaxivities are not linearly dependent on μ but on μ^2. The effect of an increasing μ would be greater on the relaxivity, since the difference between μ and μ^2 is greater.

Knowing this, the difference between the core diameters of Polysciences 19631 and Polysciences 19632 must not be that great because the difference of relaxivities is about 5%. On the other hand, one would assume that the core diameter of Polysciences 19633 is much greater than the other two because its relaxivities are more than doubled ($750(s*mM)^{-1}$ as compared to $300(s*mM)^{-1}$).

Another point to consider is the MI samples (Graphs of E, F, G, and K). These particles contain a polymer matrix with small Fe_xO_y crystals as illustrated in Figure 6. Only two forms of iron oxide are magnetic, Fe_3O_4 (magnetite) and γ-Fe_2O_3 (γ-maghemite). This being the case, these are the only possible crystals that could be in the matrix because they are the only ones that would have a magnetic effect. The magnetic moments of both are known[21].

$$Fe_3O_4 \qquad \mu_s=98Gcm^3/g$$

$$\gamma\text{-}Fe_2O_3 \qquad \mu_s=65Gcm^3/g$$

μ_s is the magnetic moment at high fields (the magnetic moment at the saturation point). The value of μ_s for magnetite is greater than that of maghemite and thus, the difference between their squares is much larger. Knowing this and looking at Graphs of E, F, G, and K, the MI sampleshave low relaxivities ($<25\ (s*mM)^{-1}$). This has led some to assume the crystals are made of γ-Fe_2O_3 because magnetite particles (having a larger magnetic moment) would produce a greater magnetic effect (higher relaxivities).

MASS NUMBER	ATOMIC NUMBER	SPIN NUMBER, I
Odd	Odd or Even	Half-Integrals: 1/2, 3/2, 5/2,. . .
Even	Even	0
Even	Odd	Integrals: 1, 2, 3, . . .

Table 1. Determination of nuclear spin quantum number, I, by mass number and atomic number.

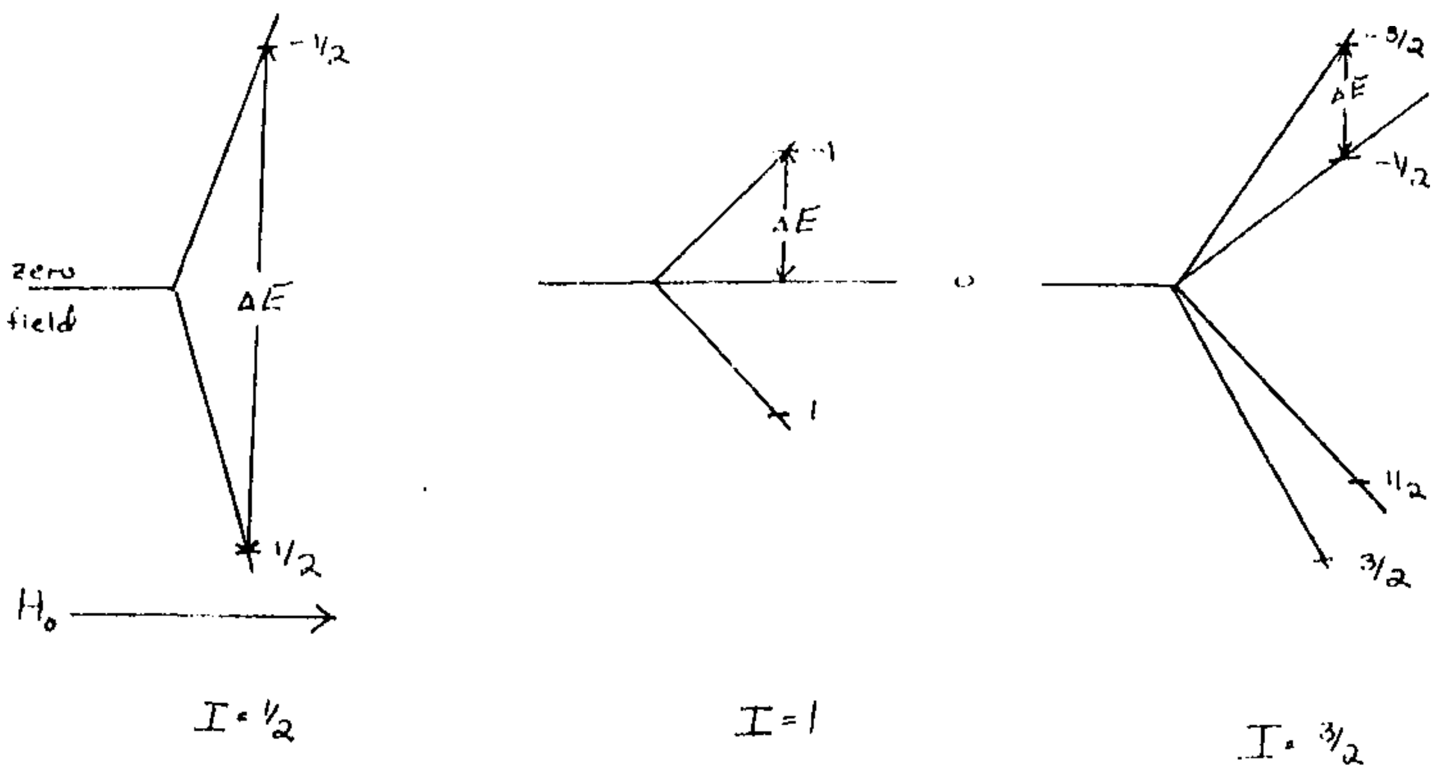


Figure 1. Nuclear Zeeman splitting of energy levels in a magnetic field for various nuclear spin quantum numbers.

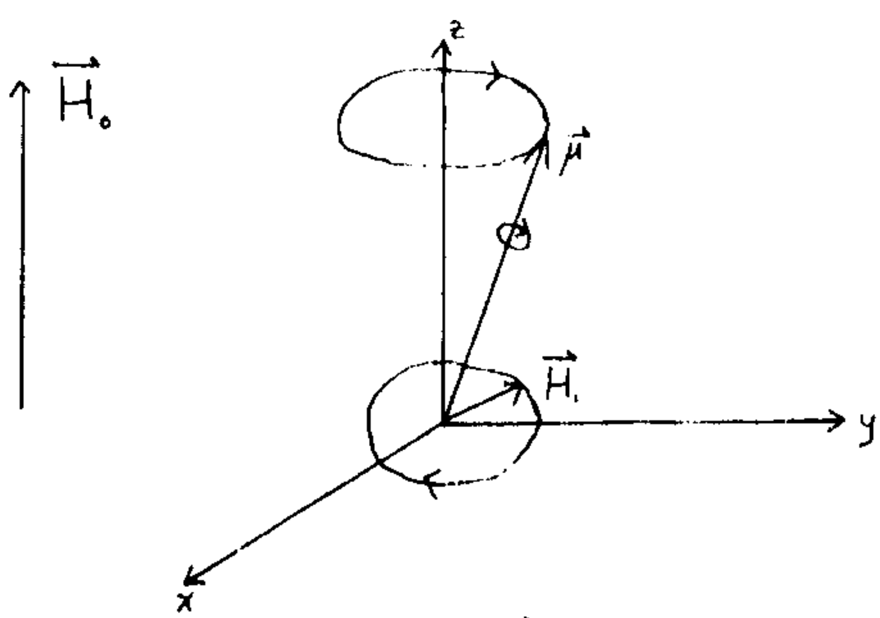


Figure 2. Precession of magnetic moment $\vec{\mu}$ in a stationary magnetic field $\vec{H}_0$ rotating at the Larmour angular frequency ω_0. $\vec{H}_1$ is a small rf field rotating with angular frequency ω.

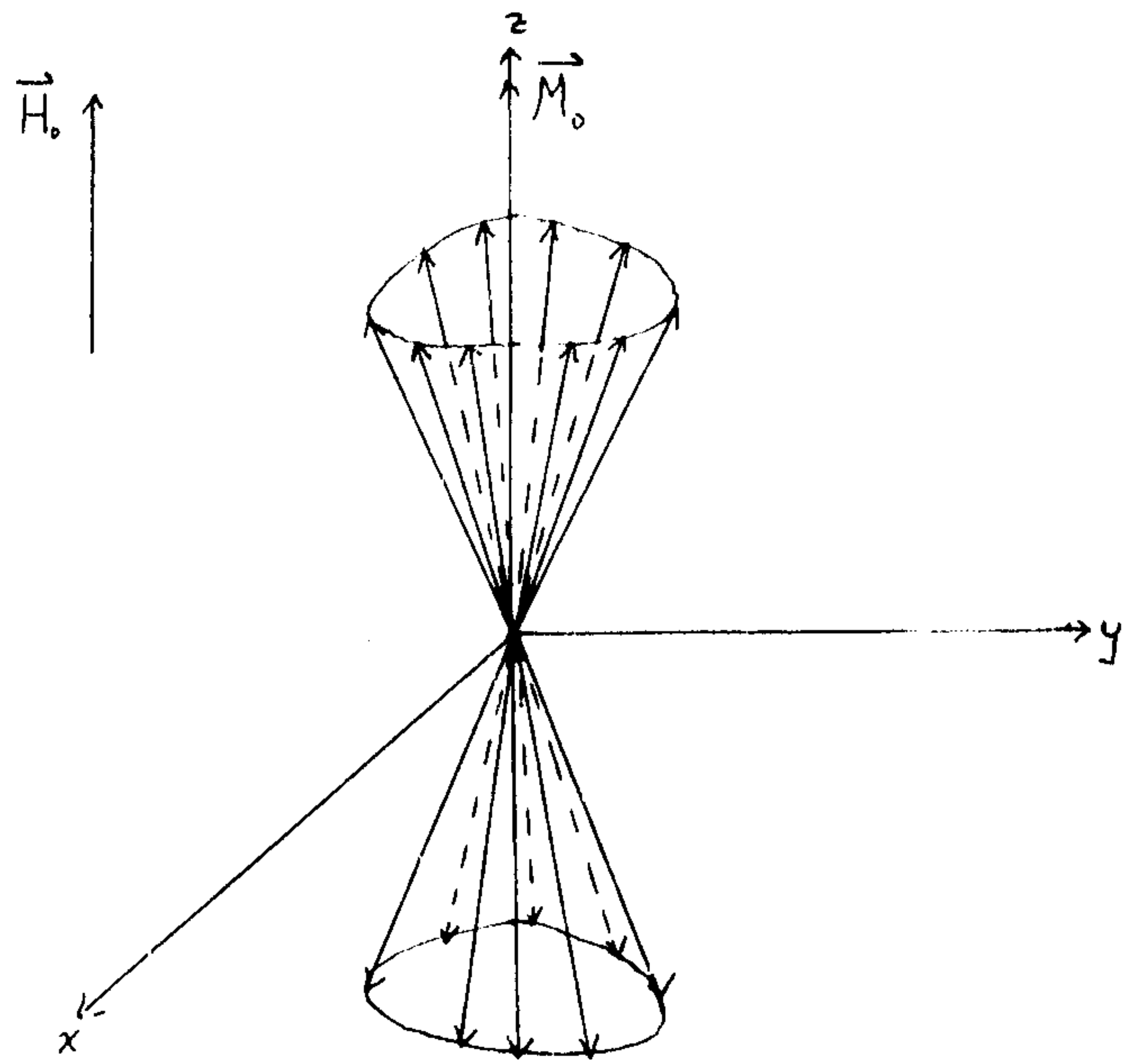


Figure 3. Orientation and precession of nuclear magnetic moments in an ensemble of nuclei with spin I=1/2, at thermal equilibrium in a stationary magnetic field $\bar{H}_0$. Direction of precession indicates $\gamma > 0$

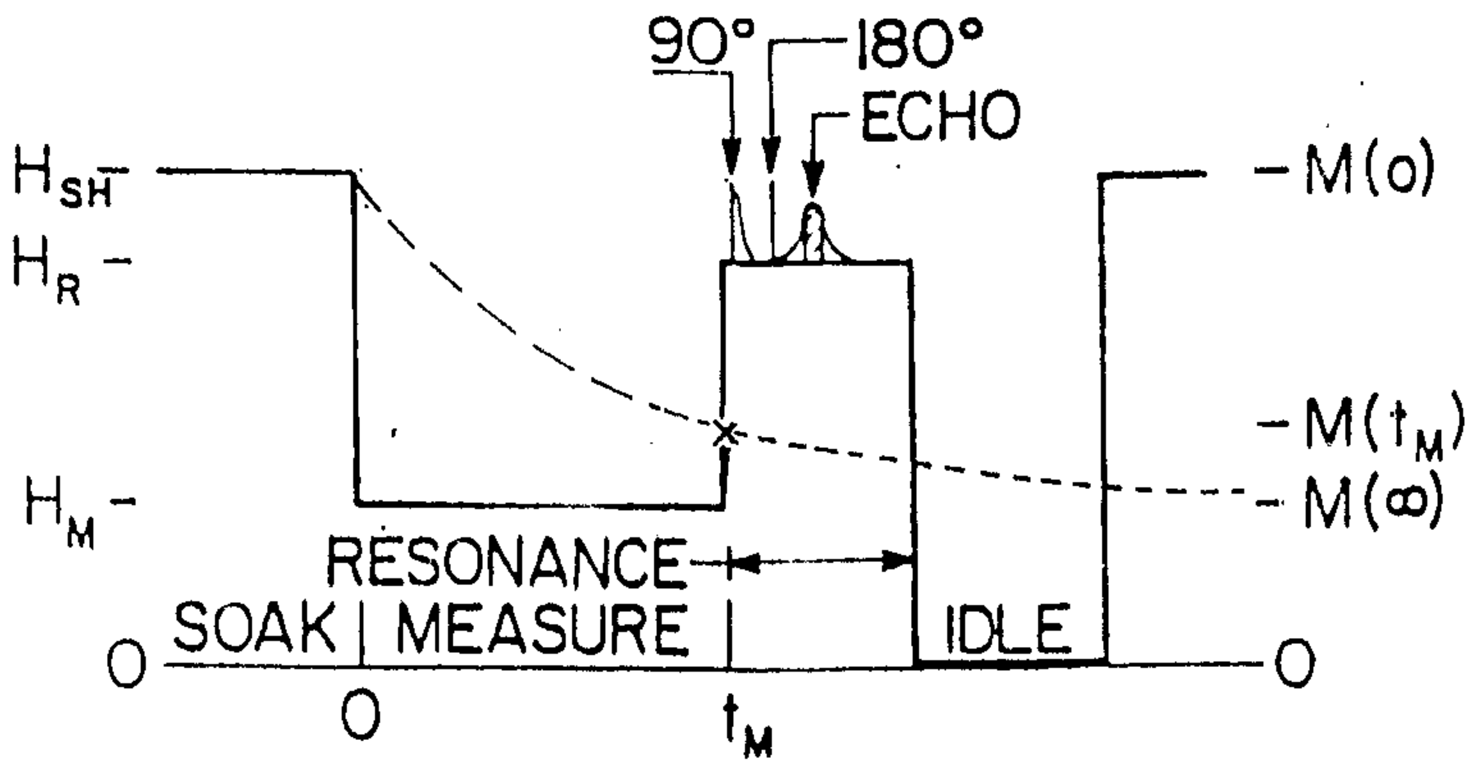


Fig. 4. Field-cycling and spin-echo sequence for measurement of T_1. The sequence is repeated for $0 < t_M \lesssim 1.5T_1$ to determine $M(t_M)$ and for $t_M \gtrsim 5T_1$ to determine $M(\infty)$. The time axis is not to scale, typical times are: soak, 0.01 to 10 sec.; measure, 0.002 to 20 sec.; resonance, 250 msec.; 90° pulse, ~ 2 μsec., 90° - 180° separation, 3 msec.; integrator gate, 1 msec.; idle, 1 to 9 sec. H_R is ~ 1 kOe; (ν_R = 4.26 MHz). (Taken from J.J. Matranga, <u>IBM Field Cycling Relaxometer - Reference Manual</u>. Appendix A, 1988).

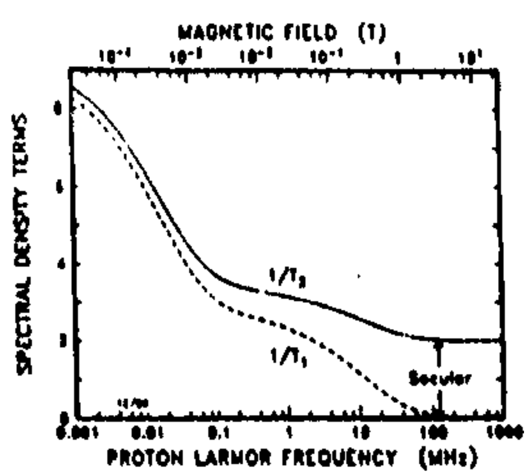
$$\frac{1}{T_1} = \left(\frac{32\pi}{405}\right)\gamma_I^2\gamma_S^2\hbar^2 S(S+1)\frac{N_A}{1000}\left(\frac{[C]}{RD}\right)[7\,j(\omega_S\tau_R) + 3\,j(\omega_I\tau_R)]$$

$$\frac{1}{T_2} = \left(\frac{32\pi}{405}\right)\gamma_I^2\gamma_S^2\hbar^2 S(S+1)\frac{N_A}{1000}\left(\frac{[C]}{RD}\right)[6.5\,j(\omega_S\tau_R) + 1.5\,j(\omega_I\tau_R) + 2\,j(0)],$$

[5a]

$$j(\omega) = \mathrm{Re}\left\{\frac{1 + (1/4)(i\omega\tau_R)^{1/2}}{1 + (i\omega\tau_R)^{1/2} + (4/9)(i\omega\tau_R) + (1/9)(i\omega\tau_R)^{3/2}}\right\}.$$

[5b]



[5c]

Figure 5. 5a shows the paramagnetic contributions to the longitudinal and transverse relaxation rates. 5b shows the spectral density function (Re means the real part of). 5c is the dispersive spectral density terms of 5a where inflection points can be seen. (Taken from P. Gillis and S. Koenig. Transverse relaxation of solvent protons induced by magnetized spheres: Application to ferritin, erythrocytes, and magnetite. Mag Res Med, 5, 326-327 (1987).)

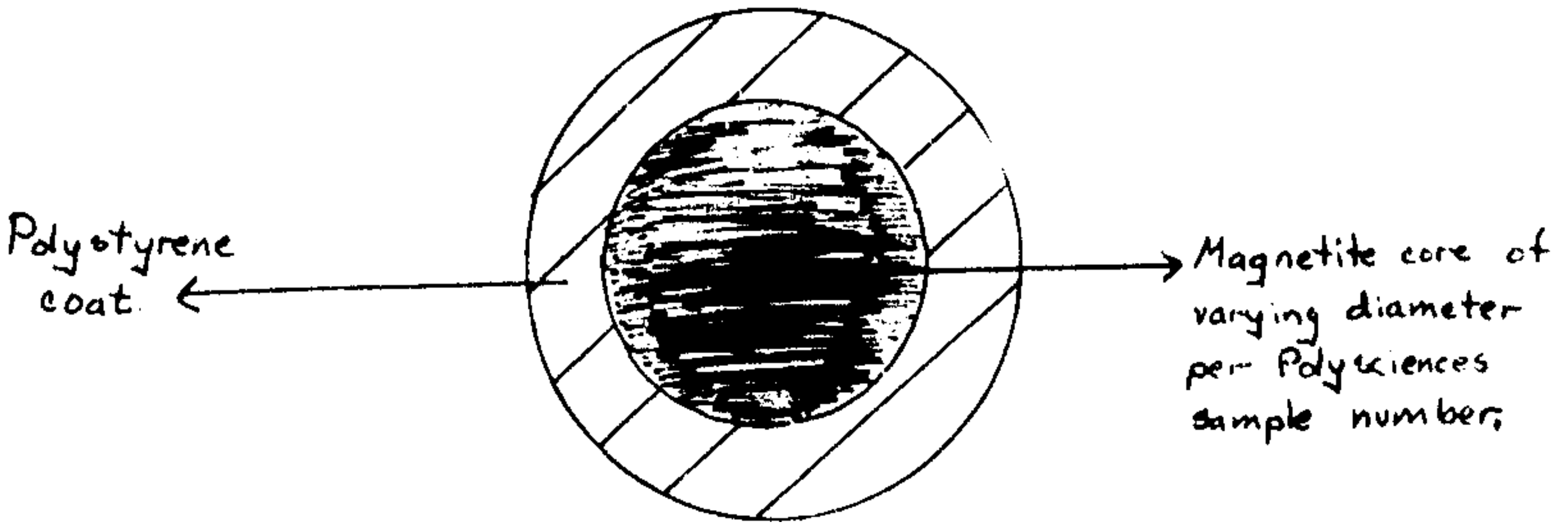


Figure 6. Illustration of magnetite coated particles.

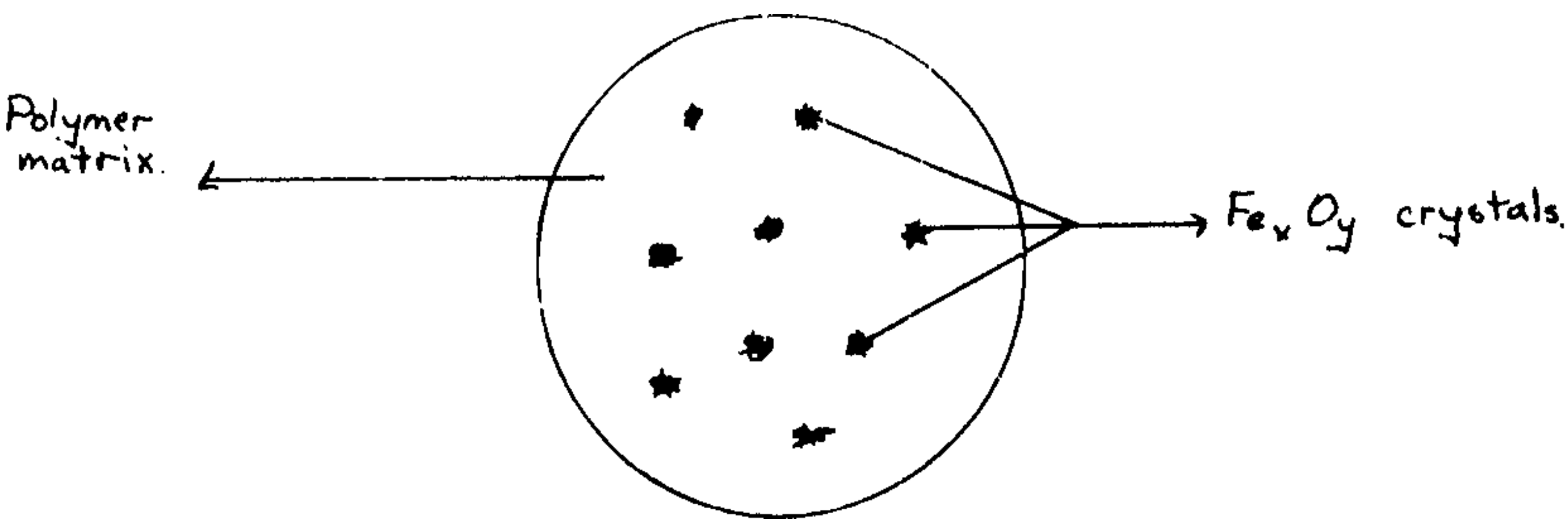


Figure 7. Illustration of superparamagnetic particles in a polymeric matrix.

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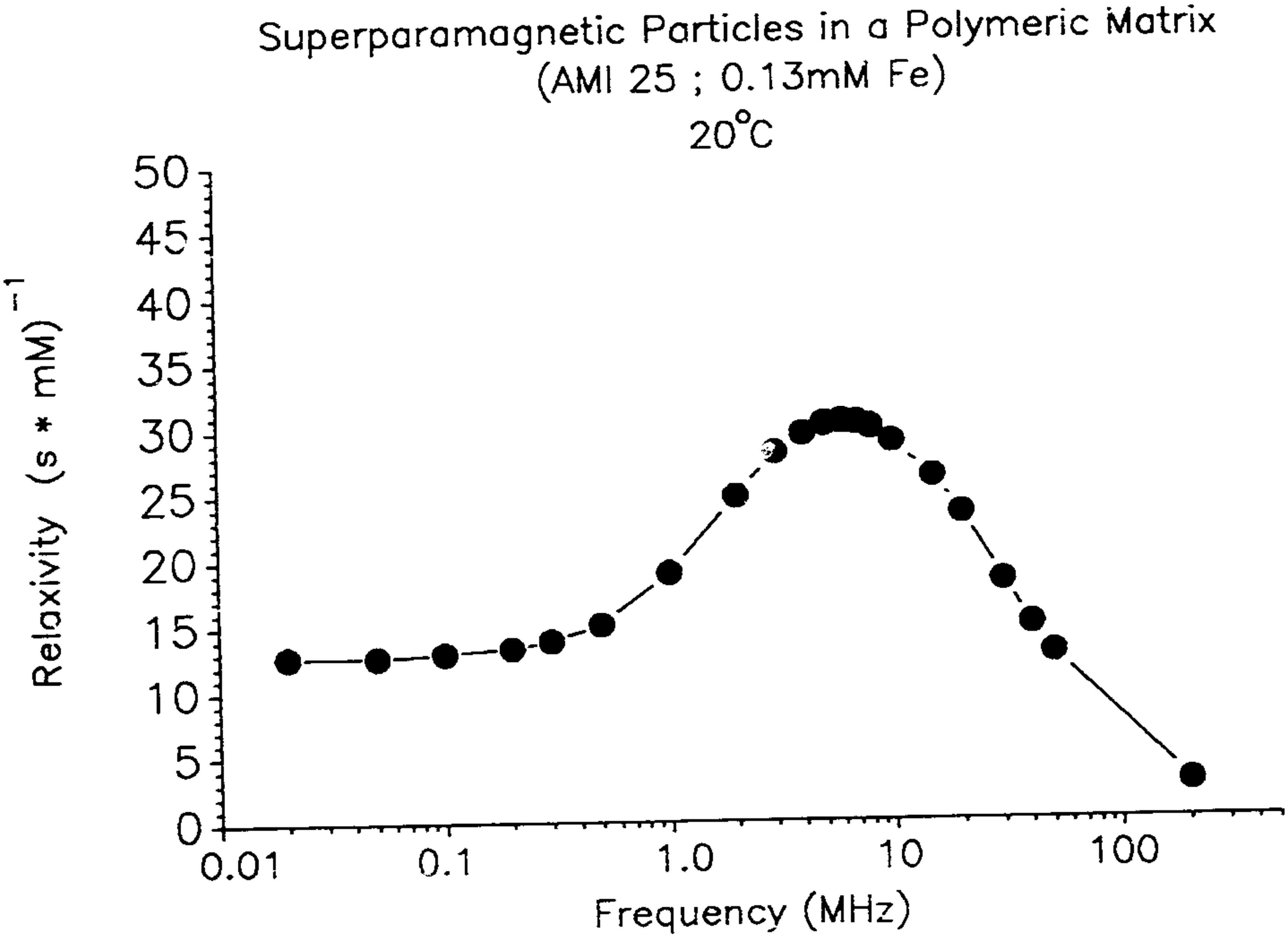
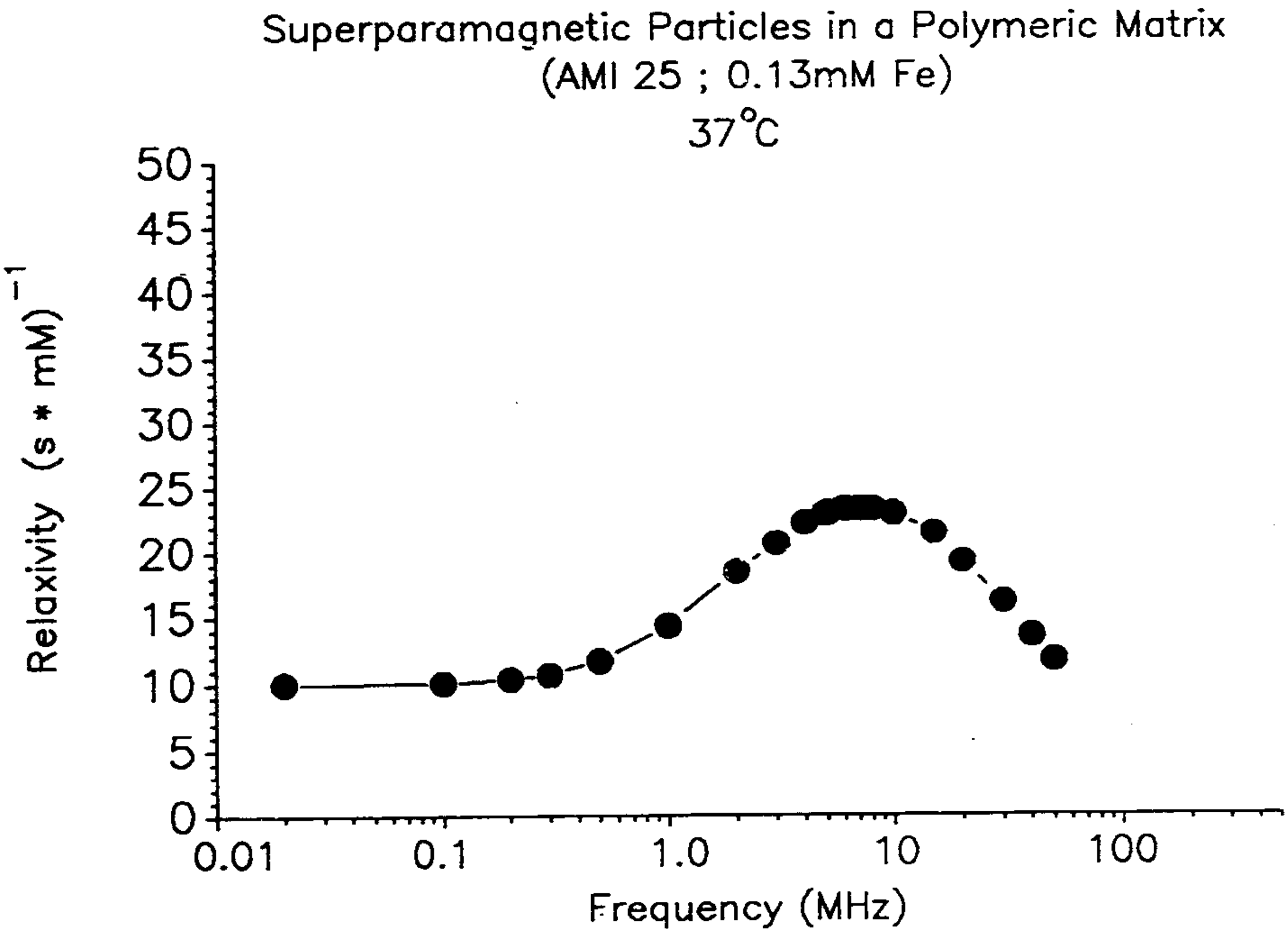
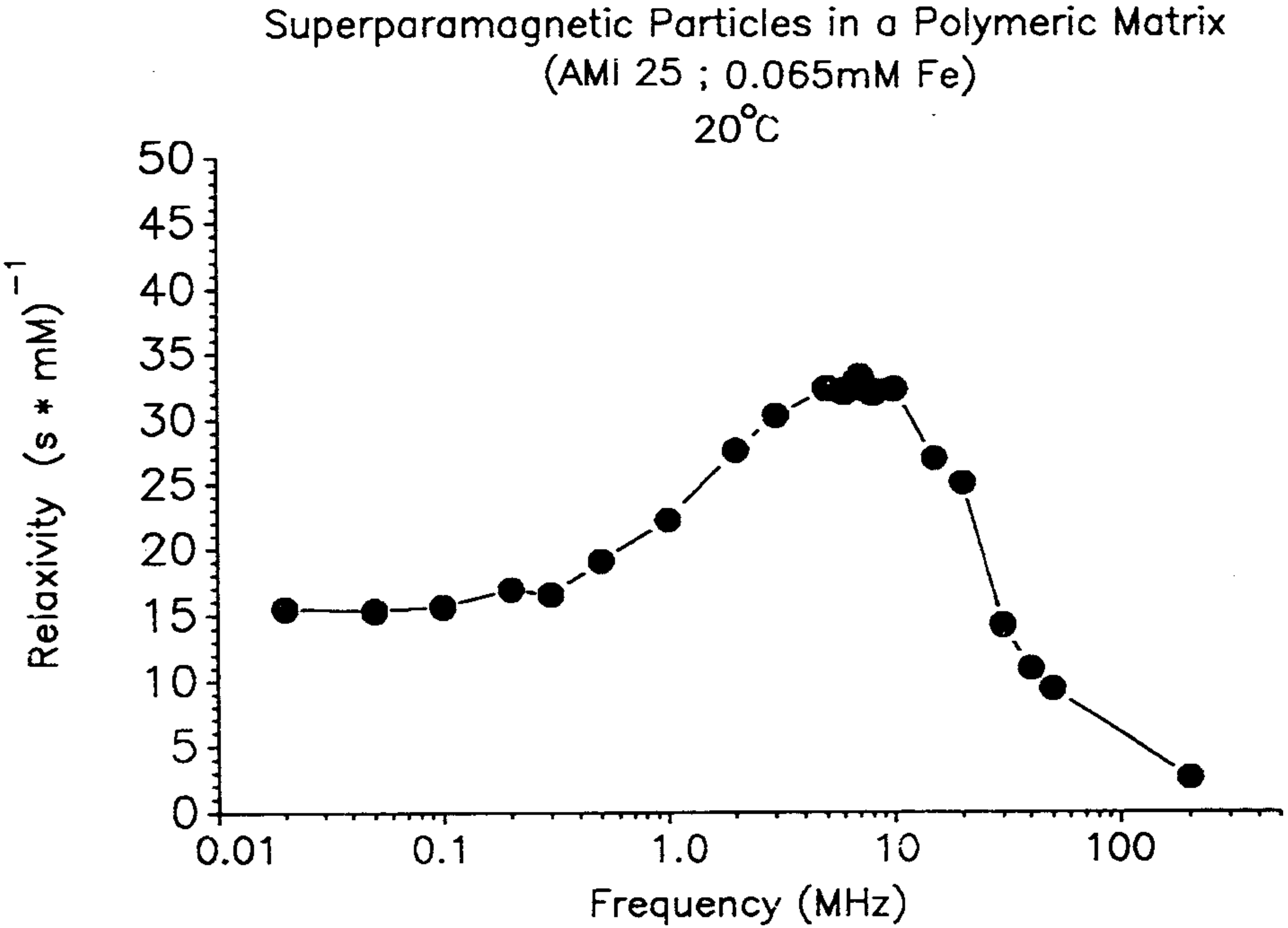

Superparamagnetic Particles in a Polymeric Matrix
(AMI 25 ; 0.13mM Fe)
20°C
Relaxivity (s * mM)^-1
50
45
40
35
30
25
20
15
10
5
0
0.01
0.1
1.0
10
100
Frequency (MHz)

A220A

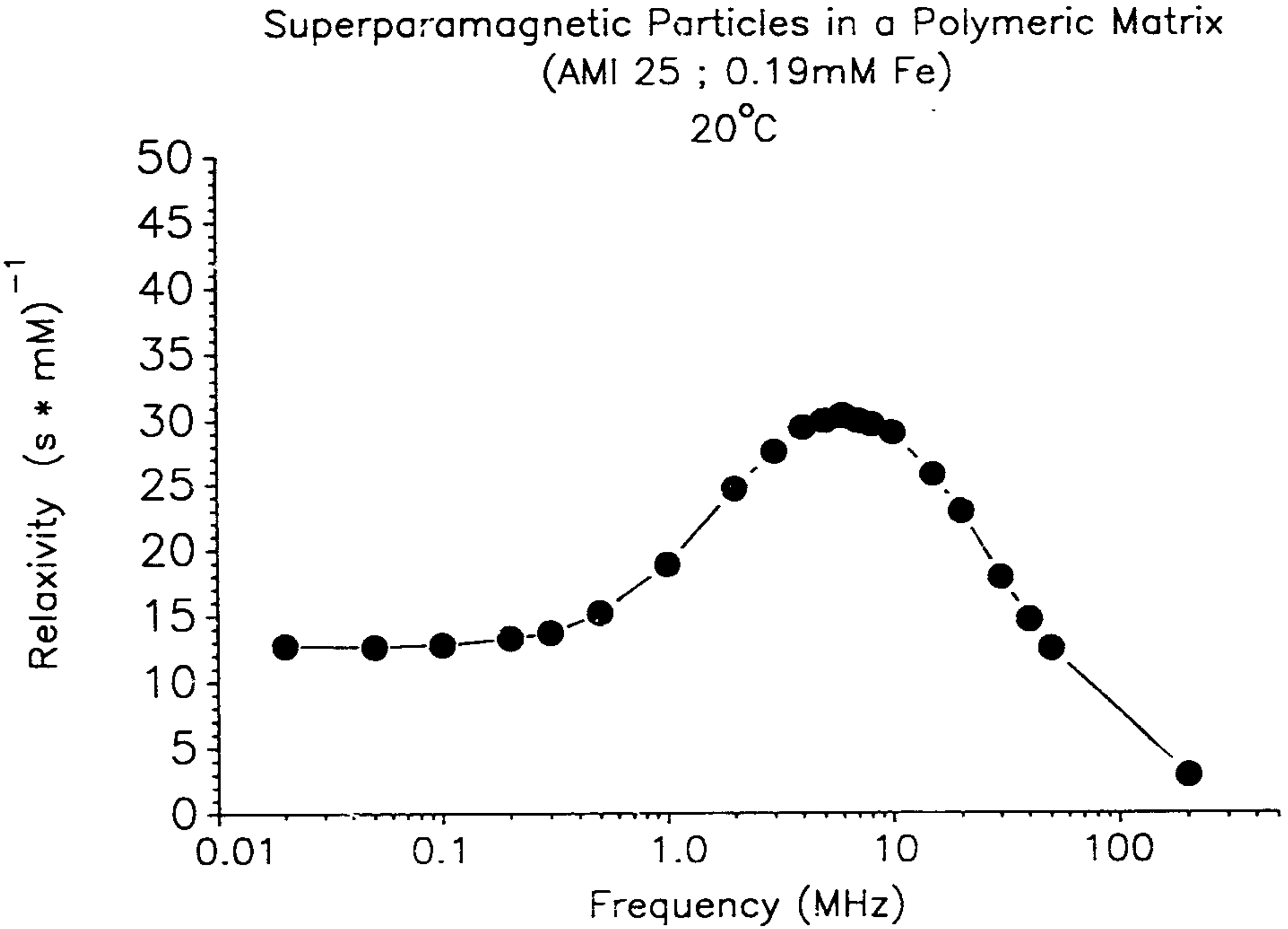


Superparamagnetic Particles in a Polymeric Matrix
(AMI 25 ; 0.13mM Fe)
37°C
Relaxivity (s * mM)$^{-1}$
50
45
40
35
30
25
20
15
10
5
0
0.01
0.1
1.0
10
100
Frequency (MHz)

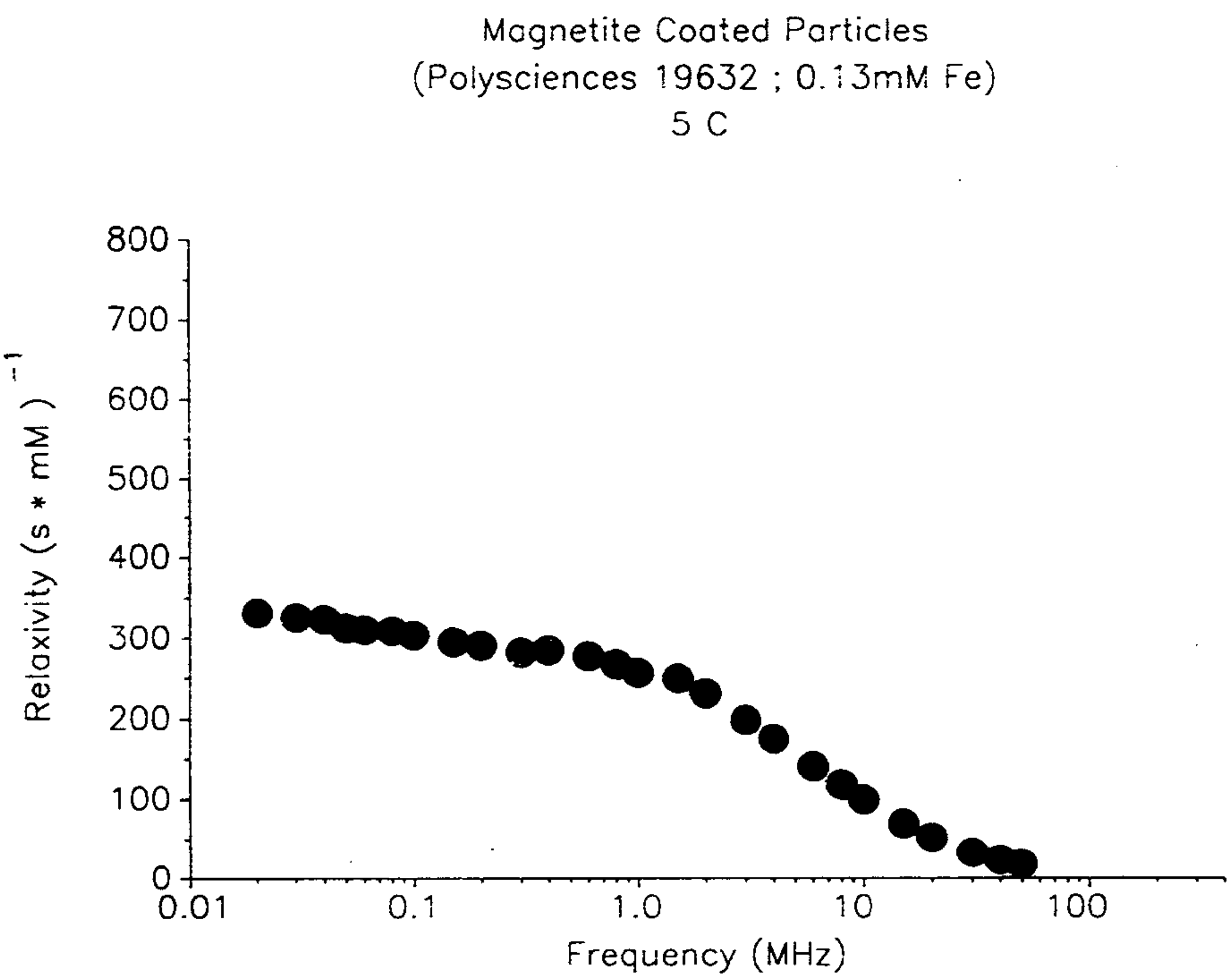
A237A


Superparamagnetic Particles in a Polymeric Matrix
(AMI 25 ; 0.065mM Fe)
20°C
Relaxivity (s * mM)$^{-1}$
50
45
40
35
30
25
20
15
10
5
0
0.01
0.1
1.0
10
100
Frequency (MHz)

A320A


Superparamagnetic Particles in a Polymeric Matrix
(AMI 25 ; 0.19mM Fe)
20°C
Relaxivity (s * mM)^-1
50
45
40
35
30
25
20
15
10
5
0
0.01
0.1
1.0
10
100
Frequency (MHz)

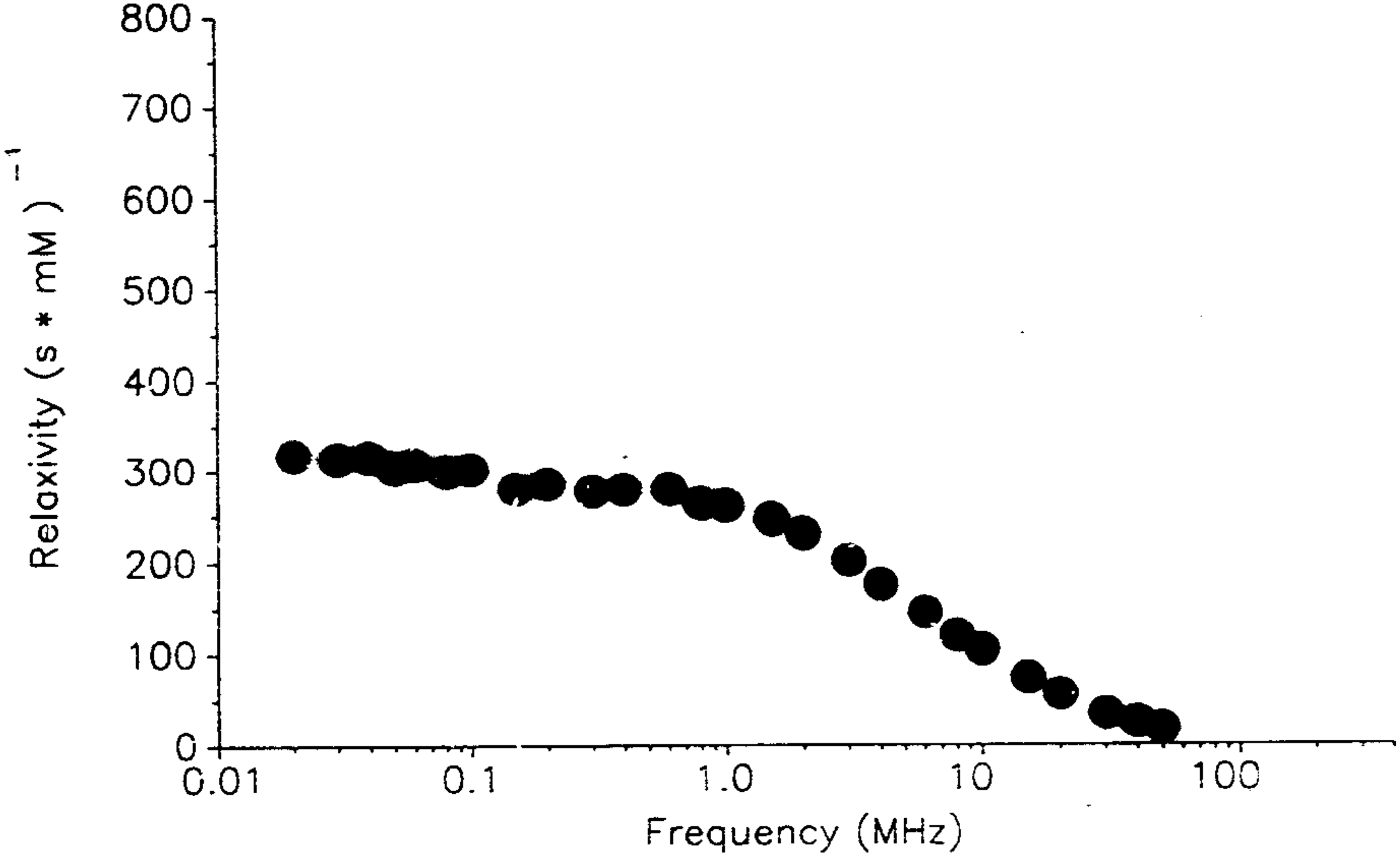
A120A

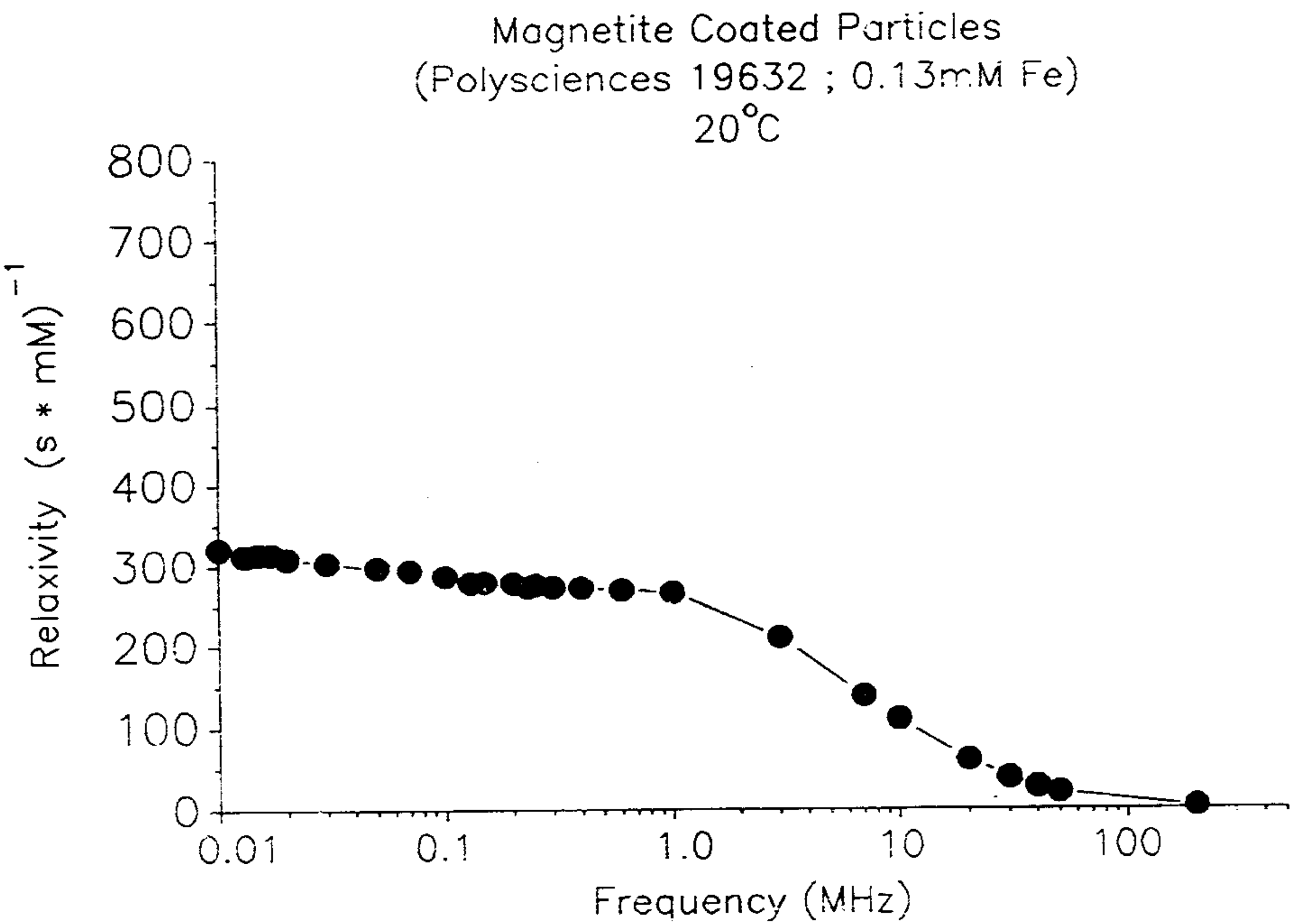


Magnetite Coated Particles
(Polysciences 19632 ; 0.13mM Fe)
5 C
Relaxivity (s * mM)$^{-1}$
800
700
600
500
400
300
200
100
0
0.01
0.1
1.0
10
100
Frequency (MHz)

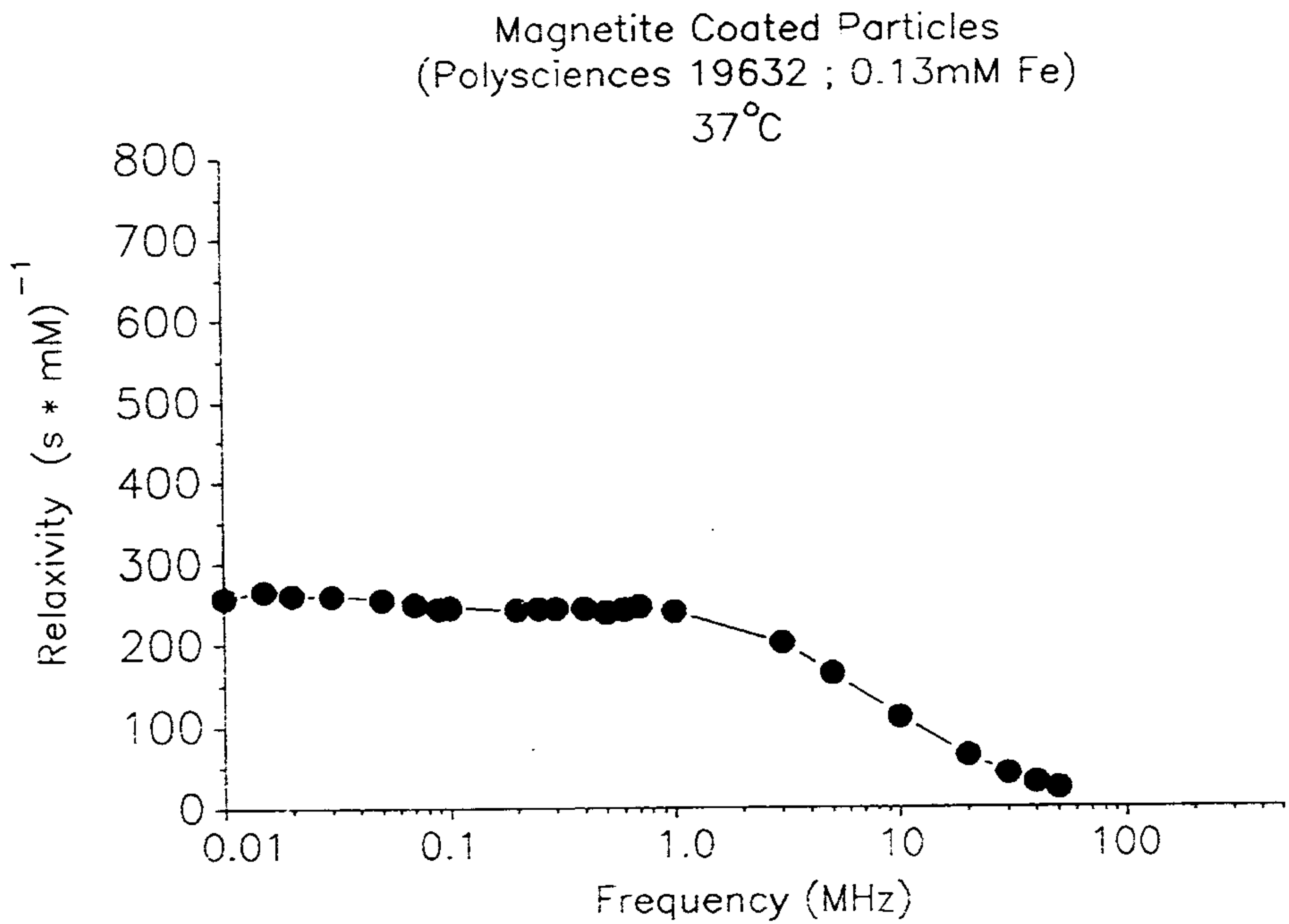
B205

Magnetite Coated Particles
(Polysciences 19632 ; 0.13mM Fe)
13C

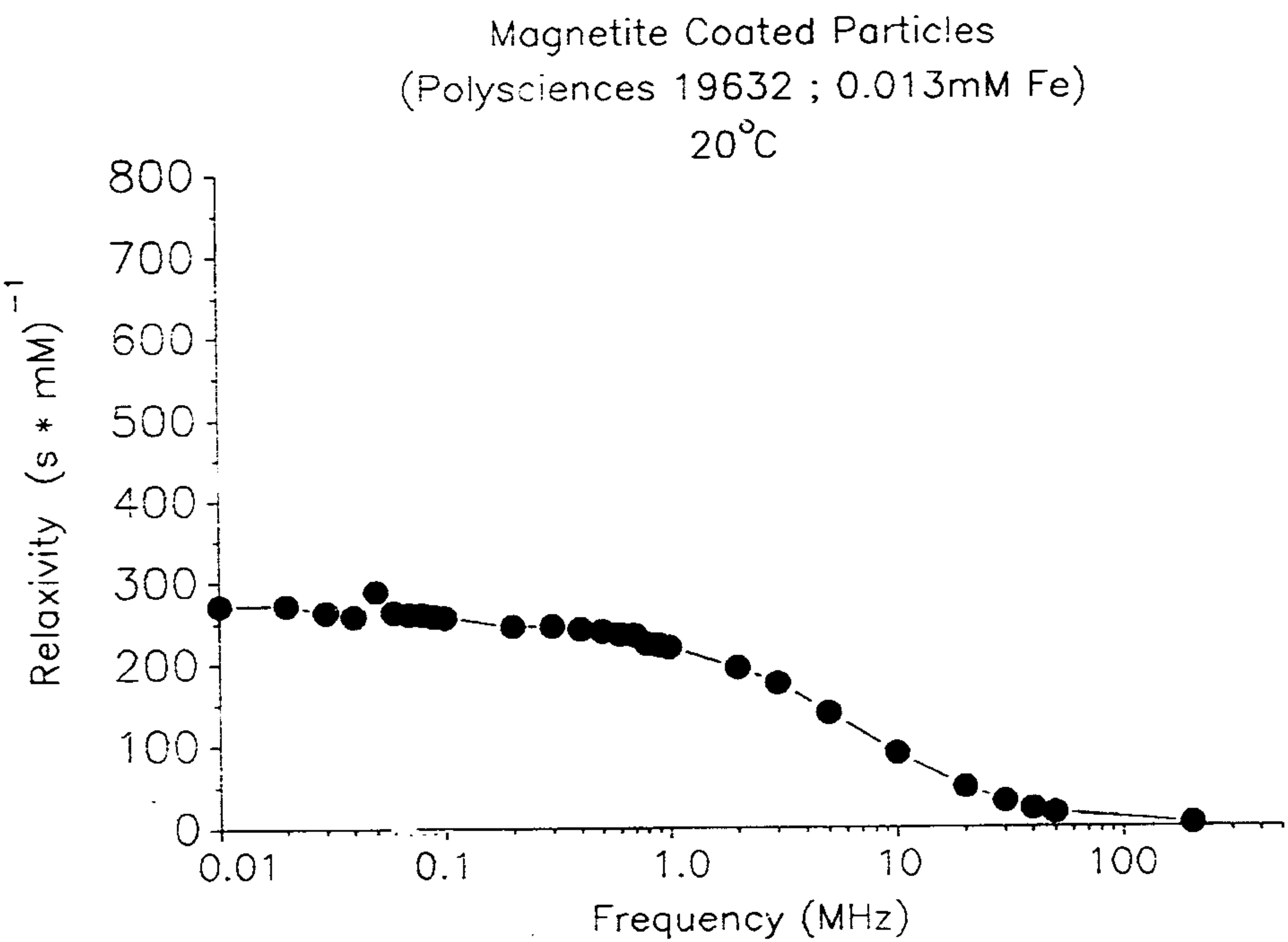



Magnetite Coated Particles
(Polysciences 19632 ; 0.13mM Fe)
20°C
Relaxivity (s * mM)^-1
800
700
600
500
400
300
200
100
0
0.01
0.1
1.0
10
100
Frequency (MHz)

B220

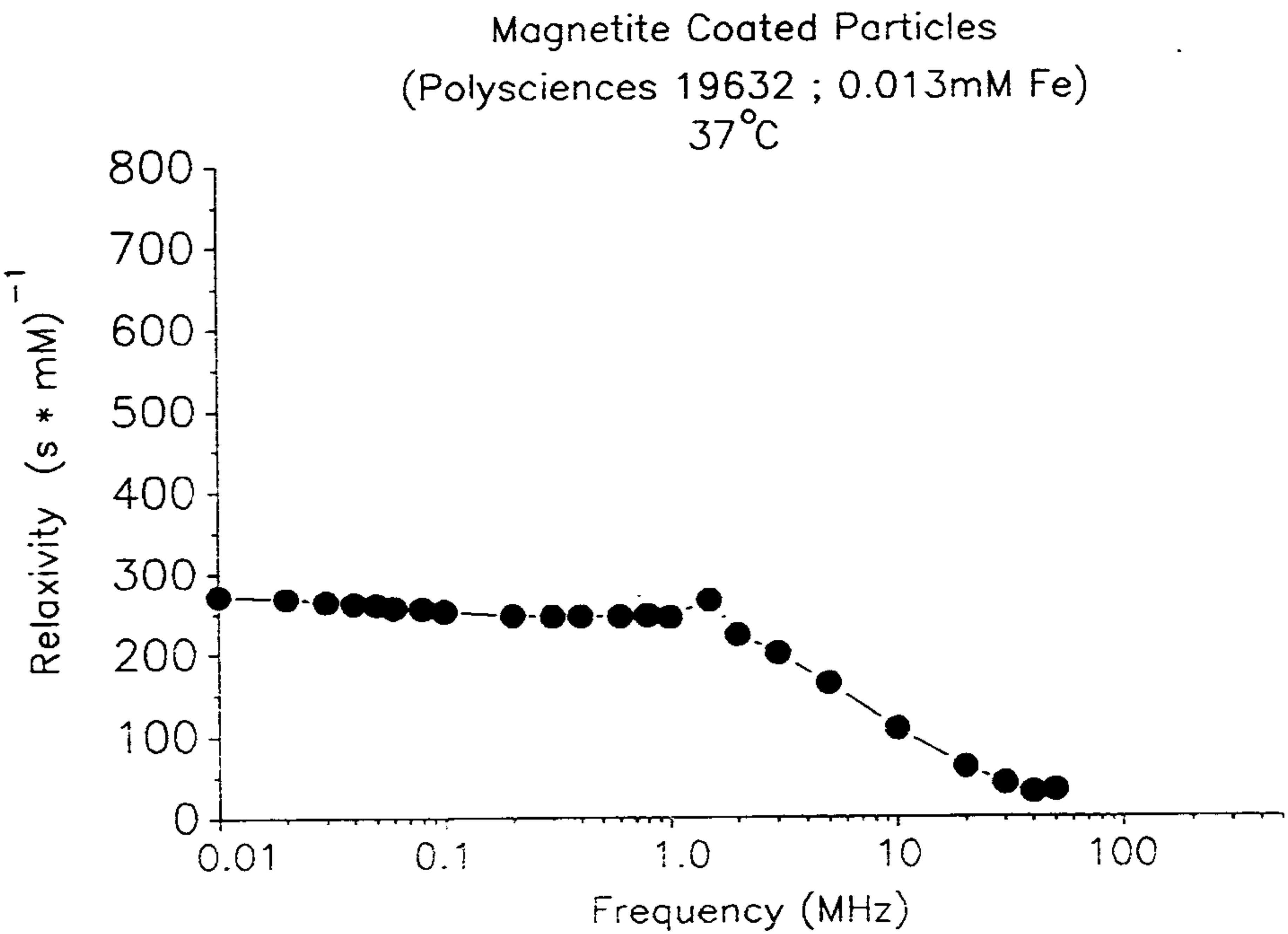

Magnetite Coated Particles
(Polysciences 19632 ; 0.13mM Fe)
37°C
Relaxivity (s * mM)$^{-1}$
800
700
600
500
400
300
200
100
0
0.01
0.1
1.0
10
100
Frequency (MHz)

B237



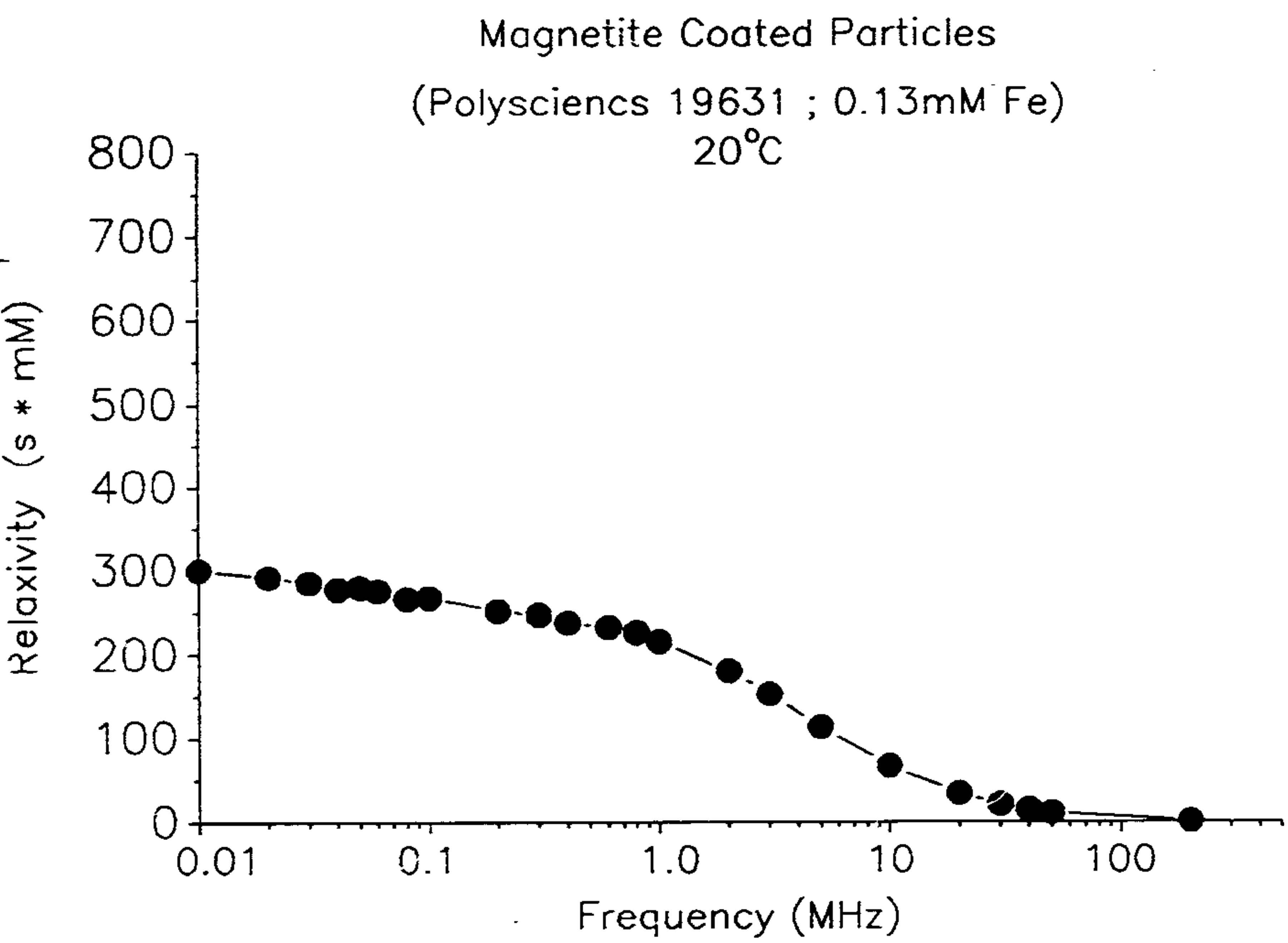
Magnetite Coated Particles
(Polysciences 19632 ; 0.013mM Fe)
20°C
Relaxivity (s * mM)$^{-1}$
800
700
600
500
400
300
200
100
0
0.01
0.1
1.0
10
100
Frequency (MHz)

B520

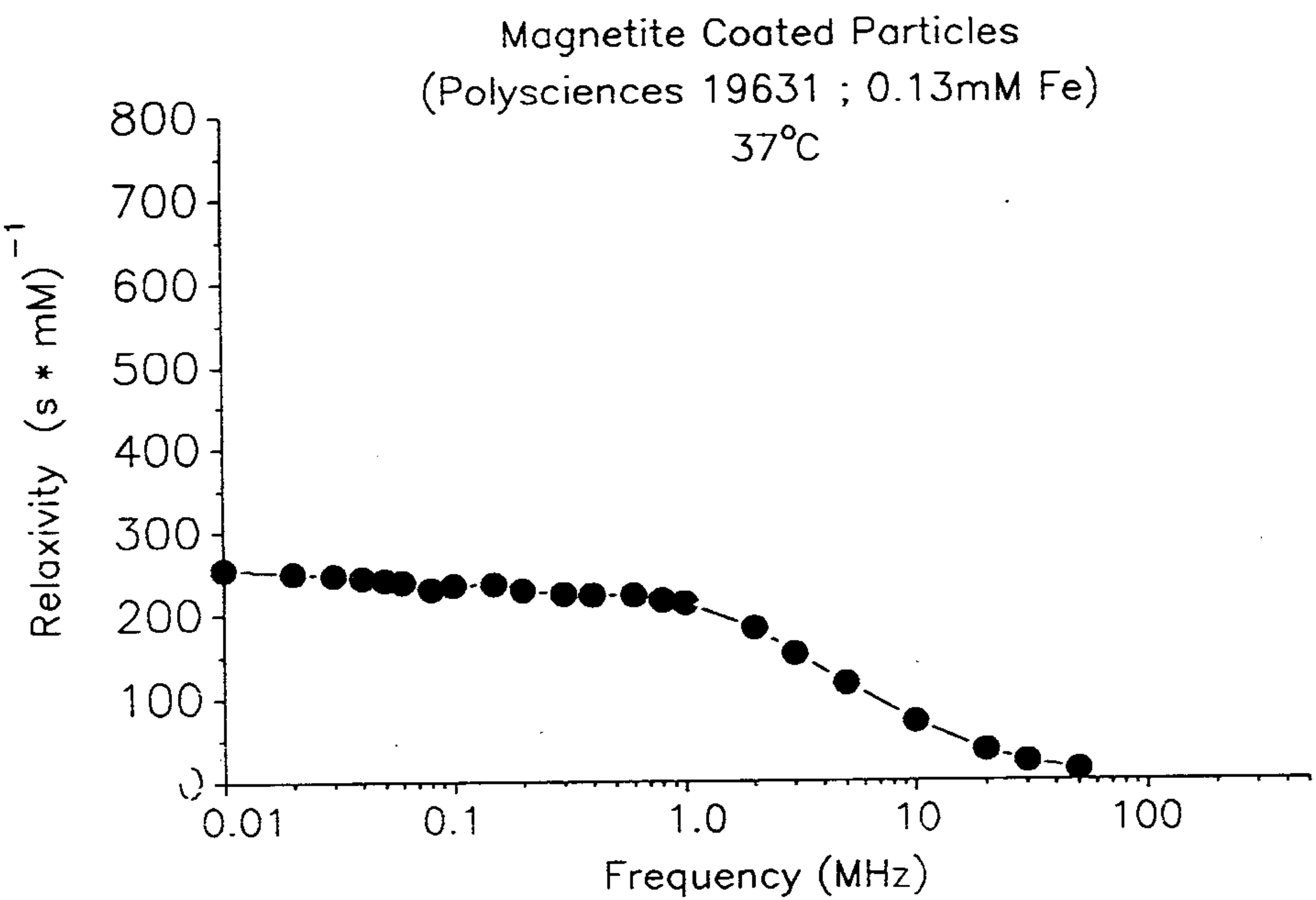


Magnetite Coated Particles
(Polysciences 19632 ; 0.013mM Fe)
37°C
Relaxivity (s * mM)⁻¹
800
700
600
500
400
300
200
100
0
0.01
0.1
1.0
10
100
Frequency (MHz)

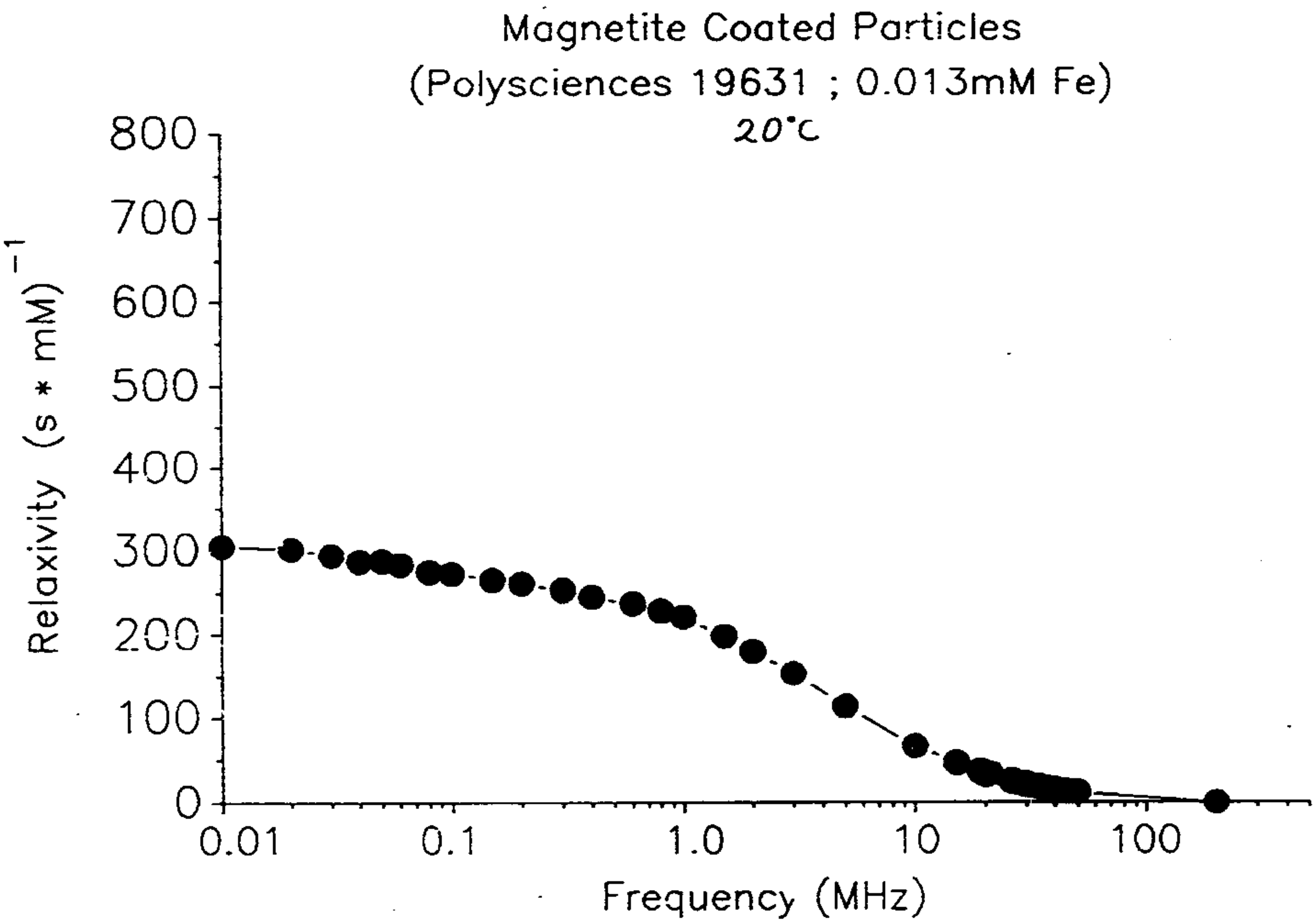
B537


Magnetite Coated Particles
(Polysciencs 19631 ; 0.13mM Fe)
20°C
800
700
600
500
400
300
200
100
0
Relaxivity (s * mM)^-1
0.01
0.1
1.0
10
100
Frequency (MHz)

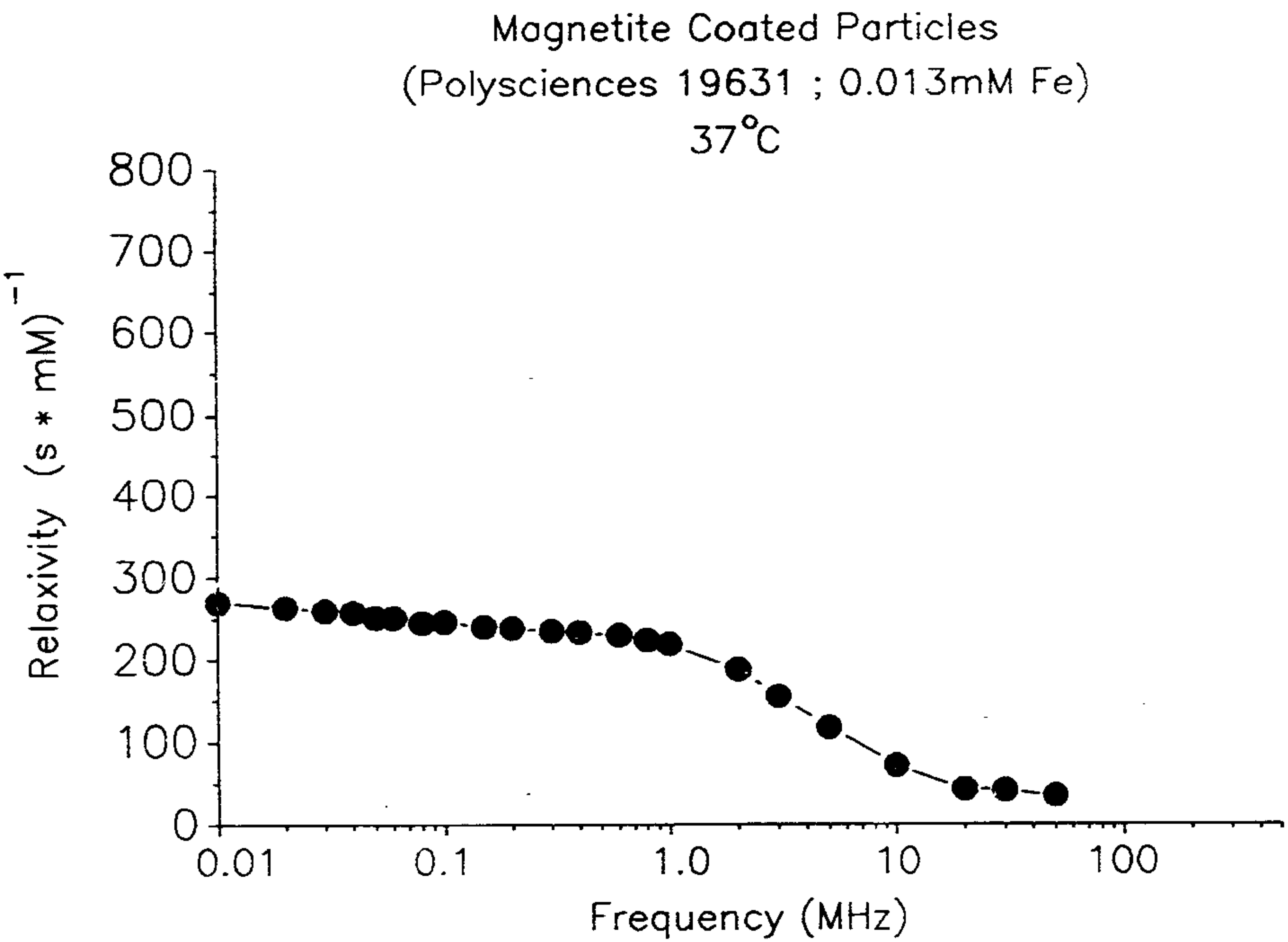
C220


Magnetite Coated Particles
(Polysciences 19631 ; 0.13mM Fe)
37°C
Relaxivity (s * mM)⁻¹
800
700
600
500
400
300
200
100
0
0.01
0.1
1.0
10
100
Frequency (MHz)

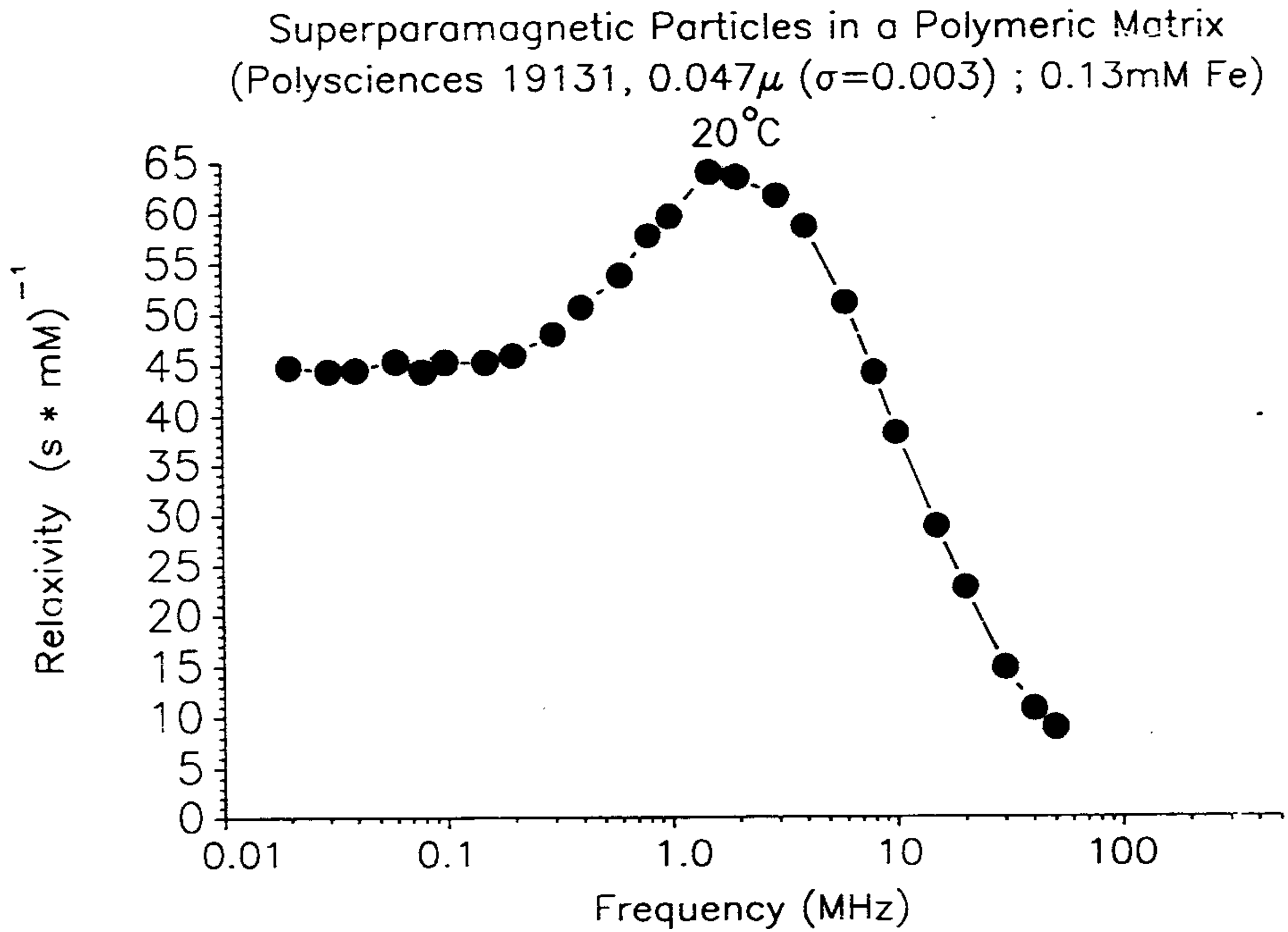
C237


Magnetite Coated Particles
(Polysciences 19631 ; 0.013mM Fe)
20°C
Relaxivity (s * mM)$^{-1}$
800
700
600
500
400
300
200
100
0
0.01
0.1
1.0
10
100
Frequency (MHz)

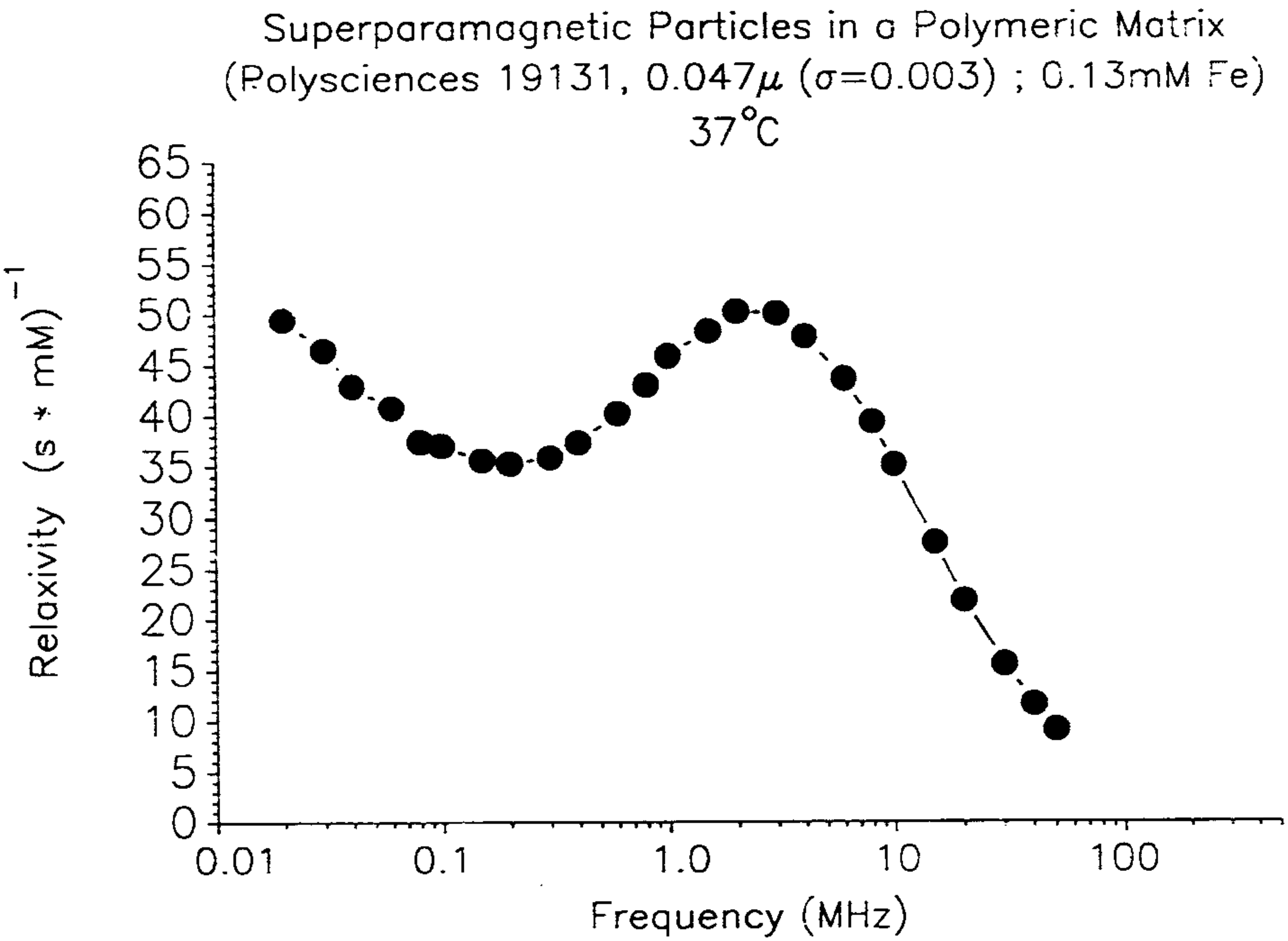
C520


Magnetite Coated Particles
(Polysciences 19631 ; 0.013mM Fe)
37°C
Relaxivity (s * mM)⁻¹
800
700
600
500
400
300
200
100
0
0.01
0.1
1.0
10
100
Frequency (MHz)

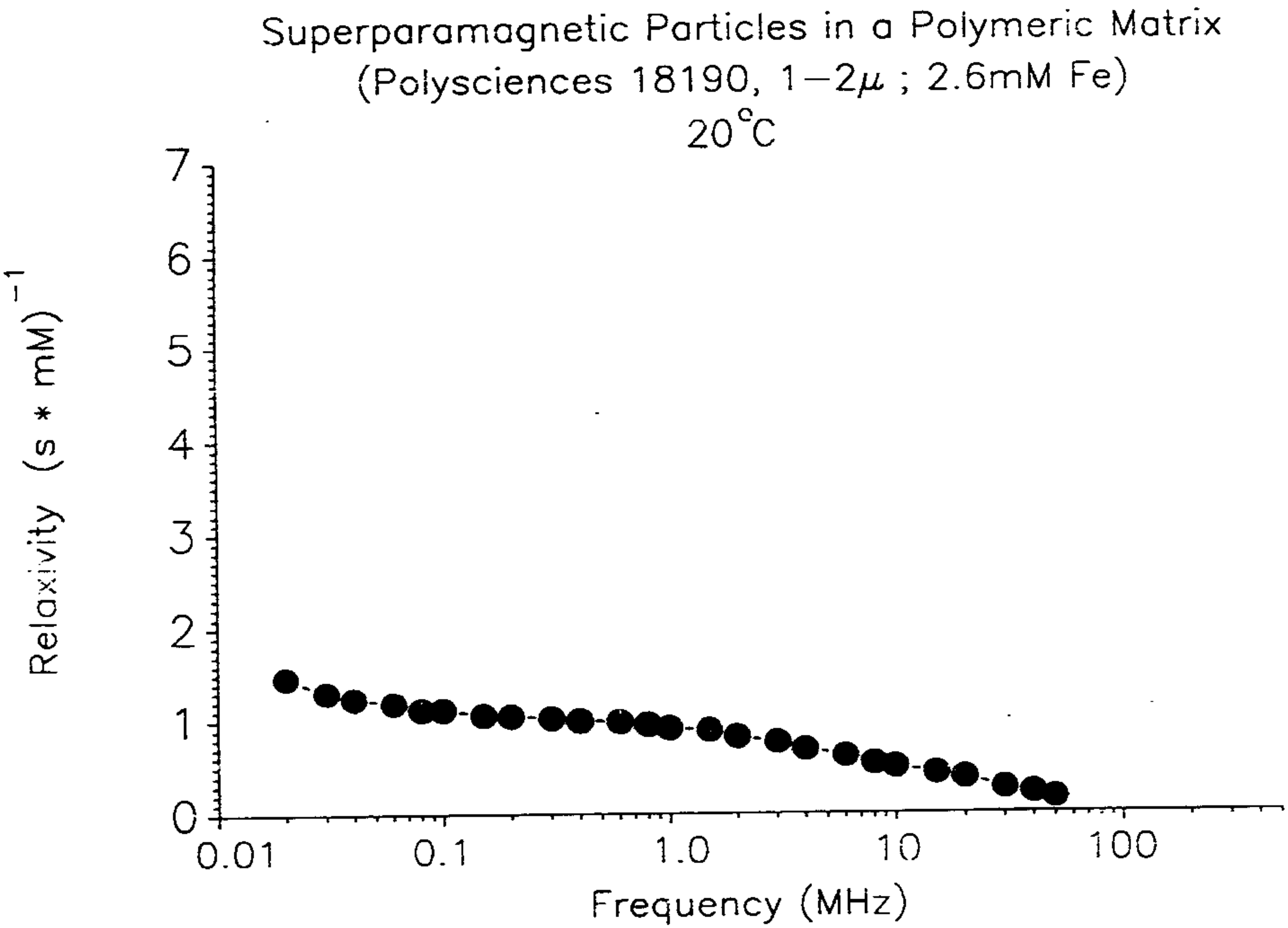
C537


Superparamagnetic Particles in a Polymeric Matrix
(Polysciences 19131, 0.047μ (σ=0.003) ; 0.13mM Fe)
20°C
Relaxivity (s * mM)$^{-1}$
65
60
55
50
45
40
35
30
25
20
15
10
5
0
0.01
0.1
1.0
10
100
Frequency (MHz)

D220

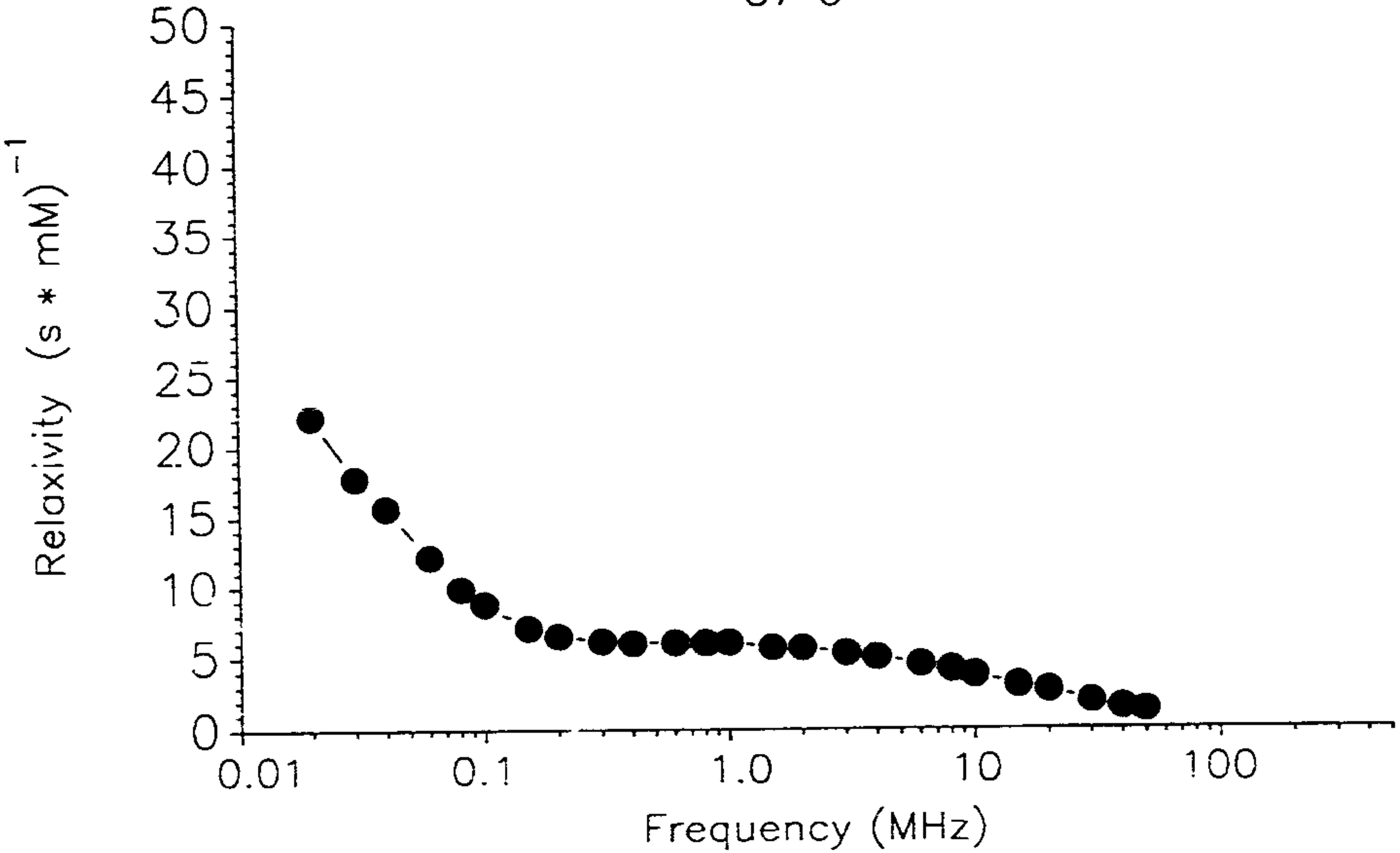

Superparamagnetic Particles in a Polymeric Matrix
(Polysciences 19131, 0.047μ (σ=0.003) ; 0.13mM Fe)
37°C
Relaxivity (s * mM)^-1
65
60
55
50
45
40
35
30
25
20
15
10
5
0
0.01
0.1
1.0
10
100
Frequency (MHz)

0237


Superparamagnetic Particles in a Polymeric Matrix
(Polysciences 18190, 1–2μ ; 2.6mM Fe)
20°C
Relaxivity (s * mM)^-1
7
6
5
4
3
2
1
0
0.01
0.1
1.0
10
100
Frequency (MHz)

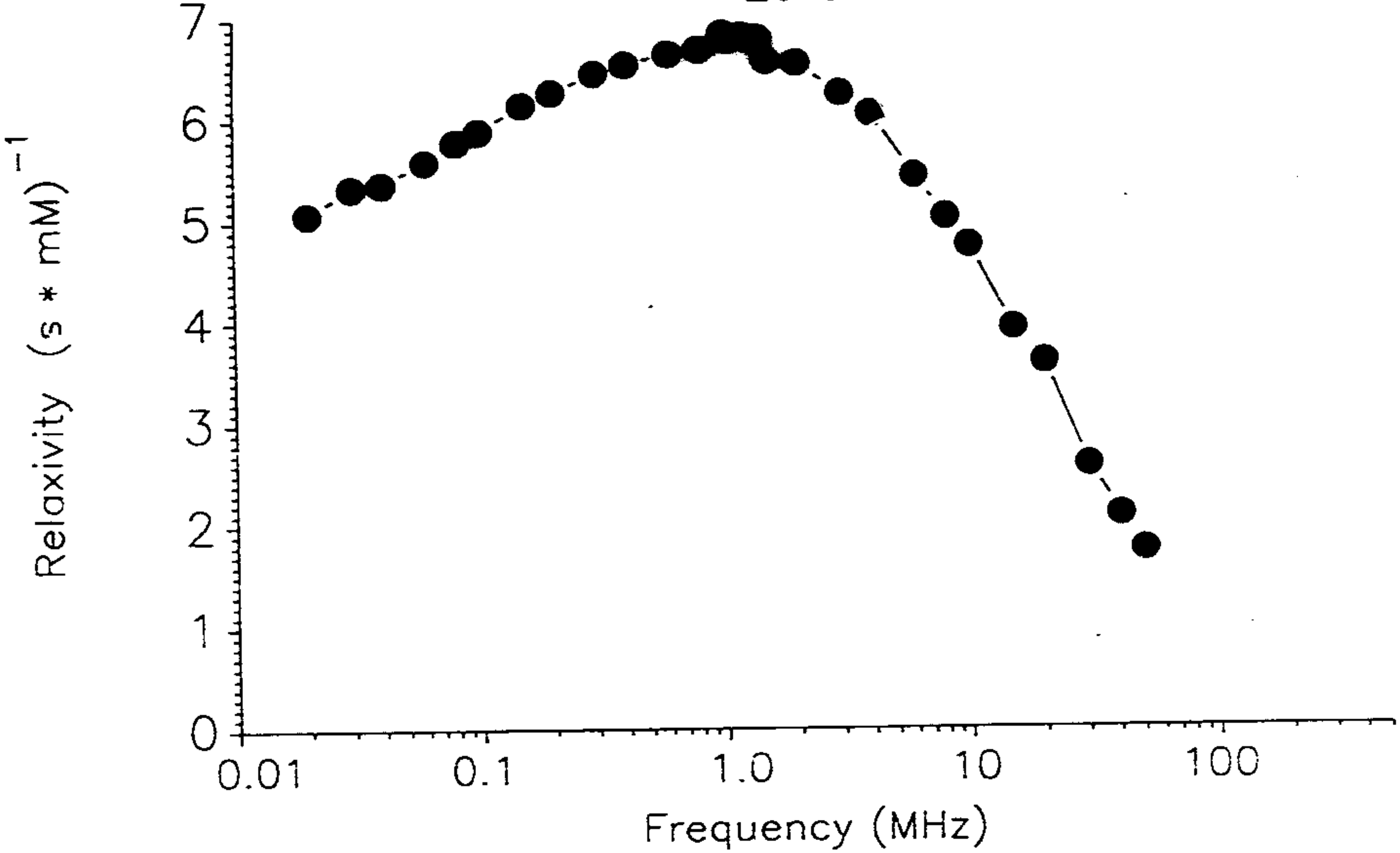
EC20

Superparamagnetic Particles in a Polymeric Matrix
(Seradyn M1180/311, 0.5–4 (1.30avg.)μ ; 0.13mM Fe)
37°C



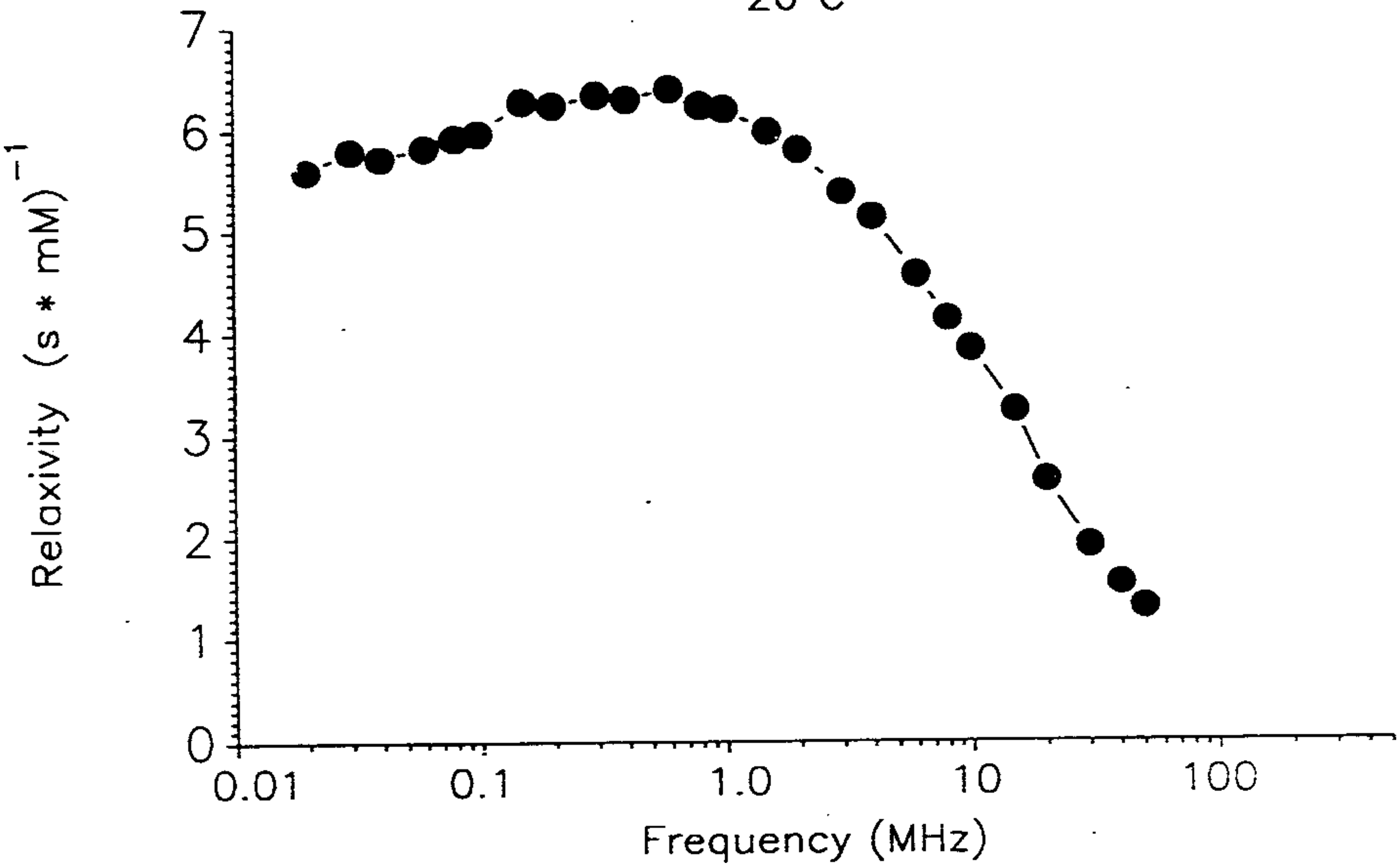
F237

Superparamagnetic Particles in a Polymeric Matrix
(Seradyn M1180/311, 0.5–4μ (1.3avg.) ; 1.3mM Fe)
20°C

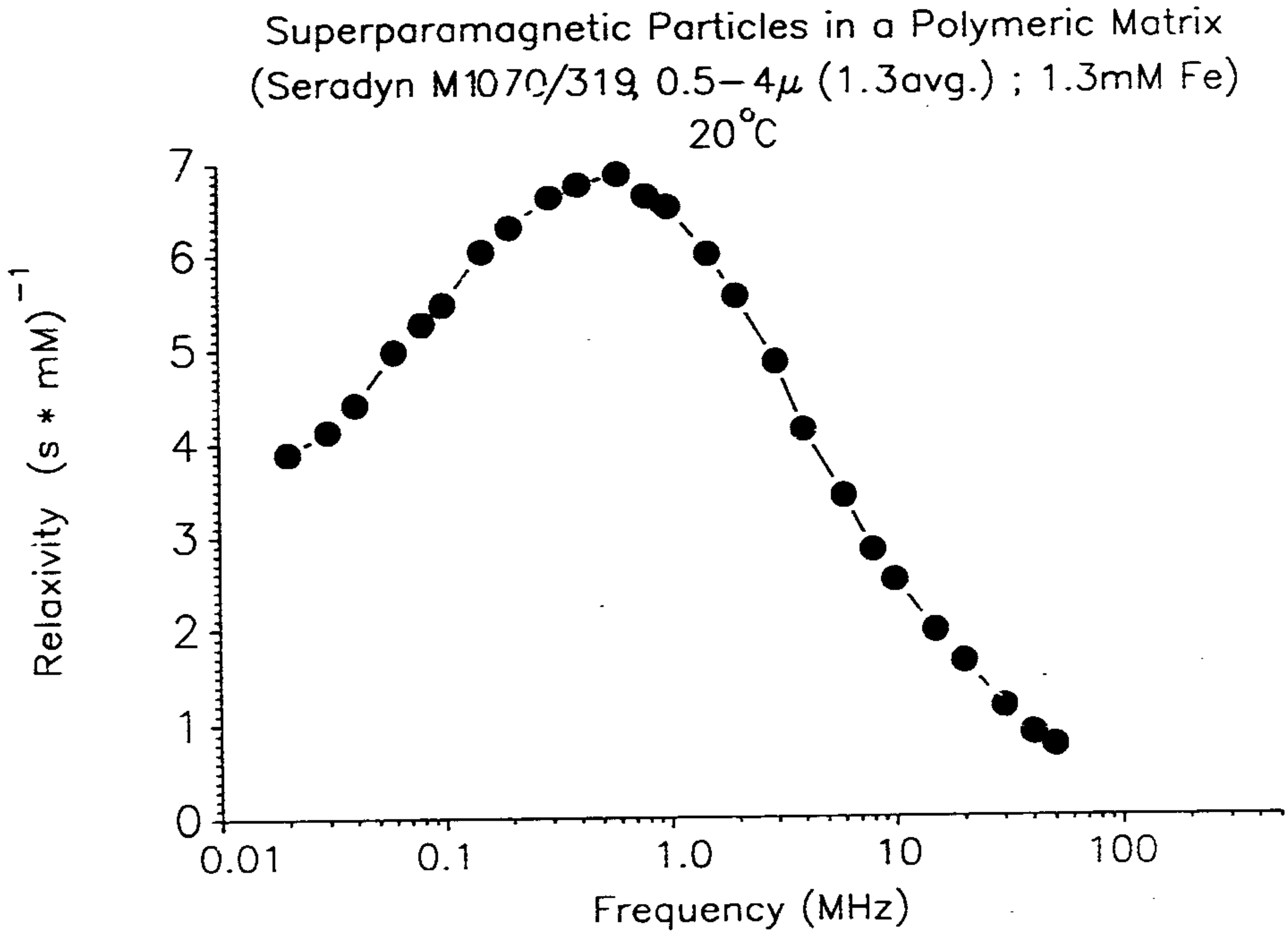


F820

Superparamagnetic Particles in a Polymeric Matrix
(Seradyn M1180/335, 0.5–5μ (1.7avg.) ; 1.3mM Fe)   23% magnetite
20°C

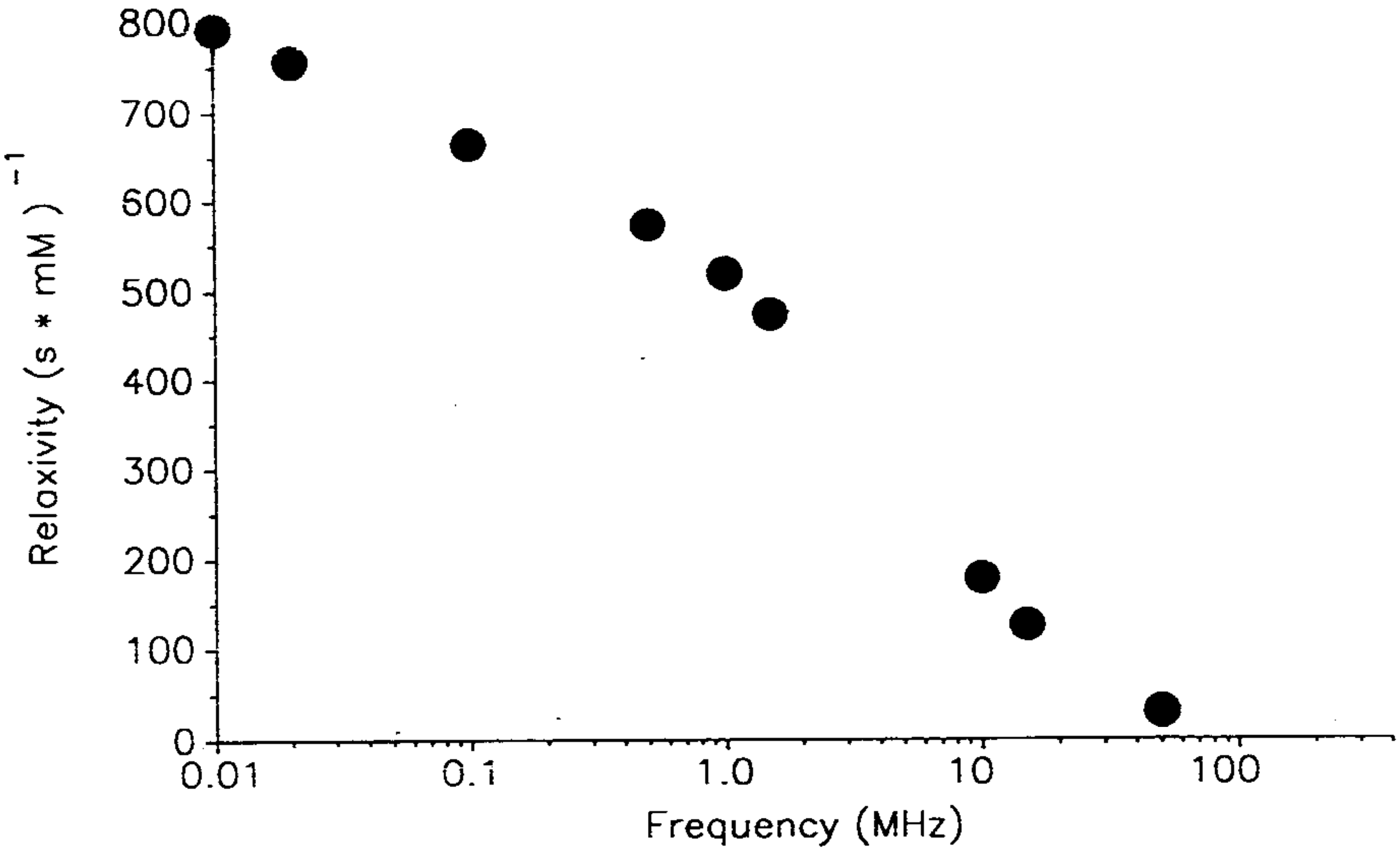


G820

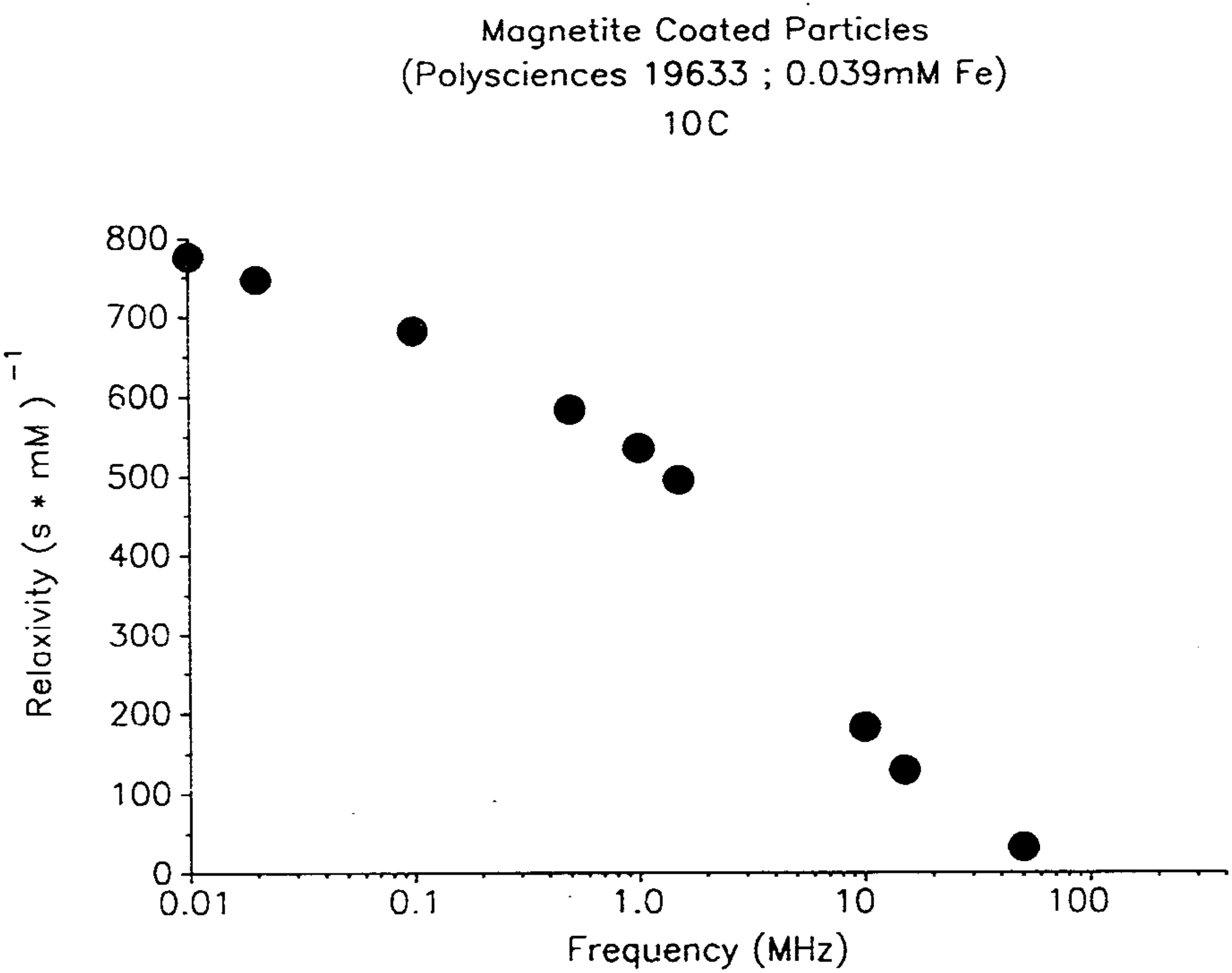

Superparamagnetic Particles in a Polymeric Matrix
(Seradyn M1070/319, 0.5–4μ (1.3avg.) ; 1.3mM Fe)
20°C
Relaxivity (s * mM)⁻¹
0
1
2
3
4
5
6
7
0.01
0.1
1.0
10
100
Frequency (MHz)

K820

Magnetite Coated Particles
(Polysciences 19633 ; 0.039mM Fe)
5 C

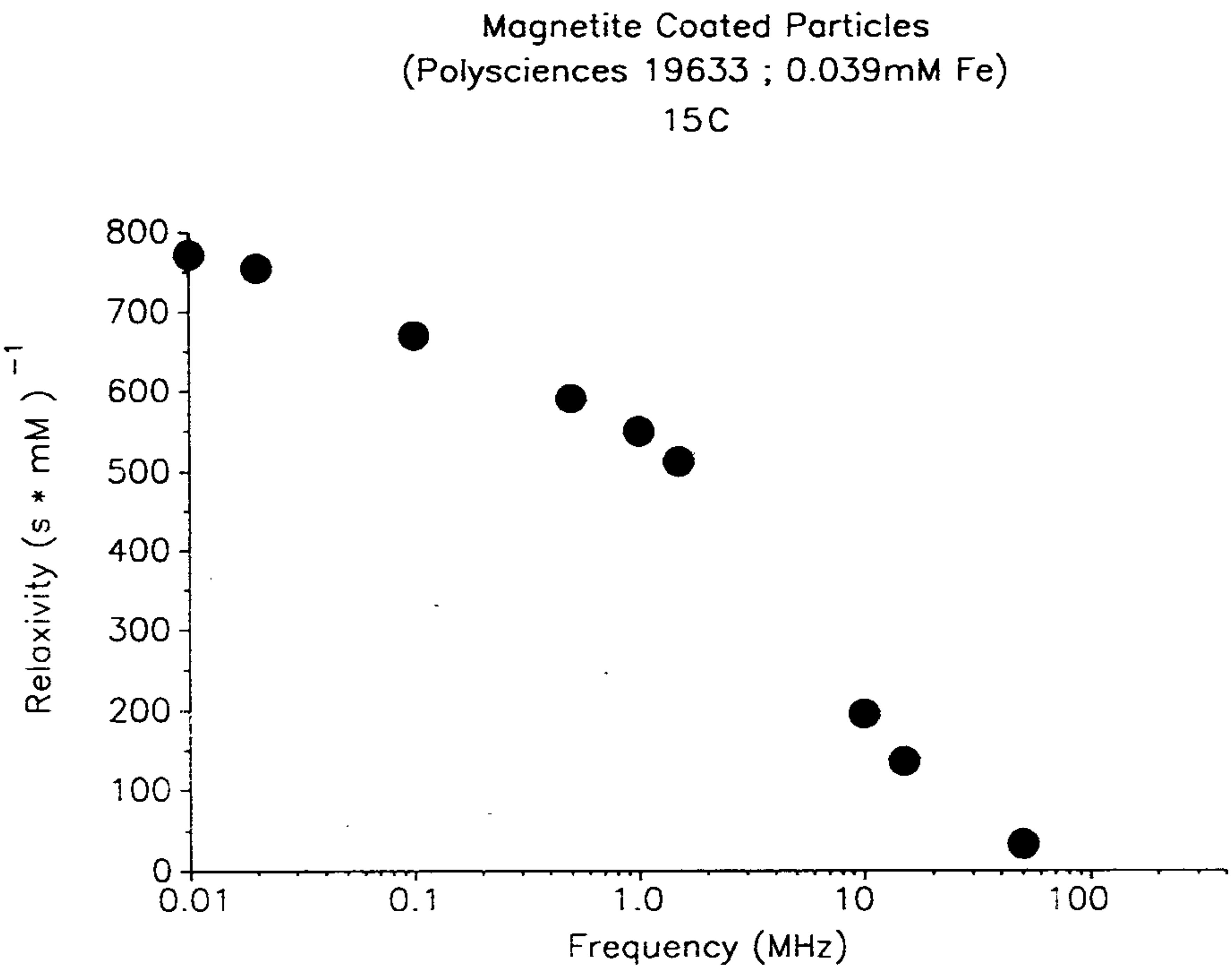


L405

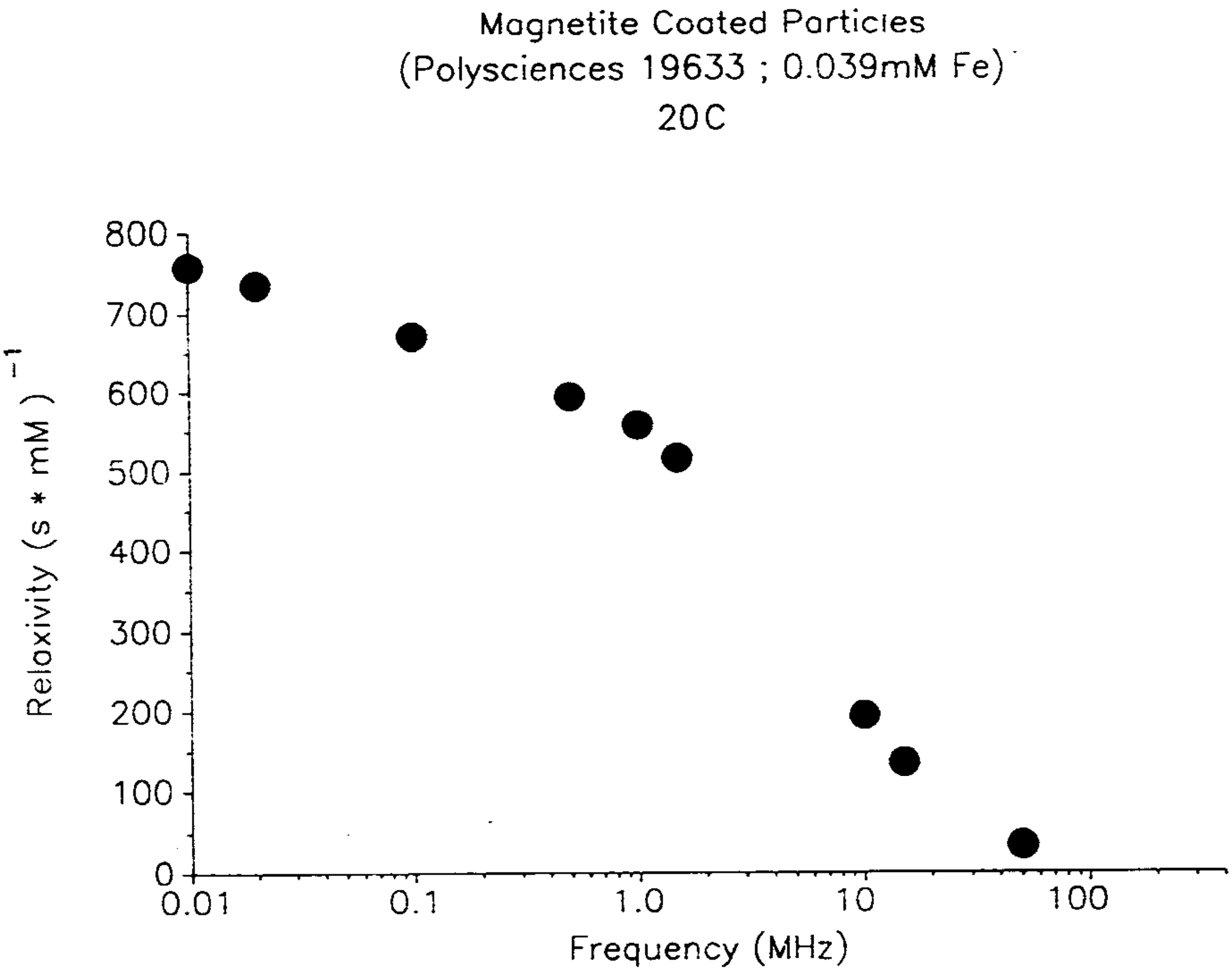


Magnetite Coated Particles
(Polysciences 19633 ; 0.039mM Fe)
10C
Relaxivity (s * mM) -1
800
700
600
500
400
300
200
100
0
0.01
0.1
1.0
10
100
Frequency (MHz)

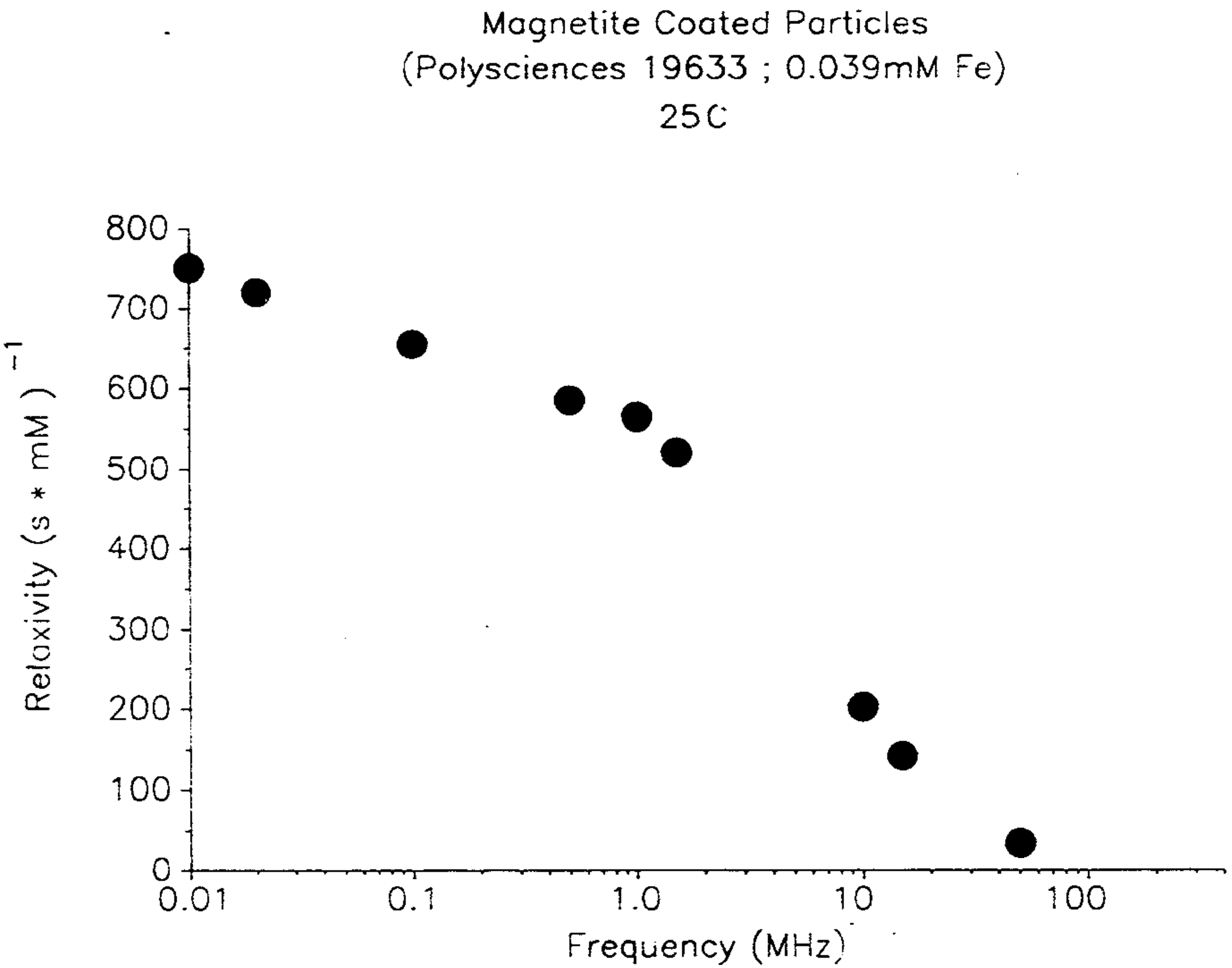
L410


Magnetite Coated Particles
(Polysciences 19633 ; 0.039mM Fe)
15C
Relaxivity (s * mM) −1
800
700
600
500
400
300
200
100
0
0.01
0.1
1.0
10
100
Frequency (MHz)

L415

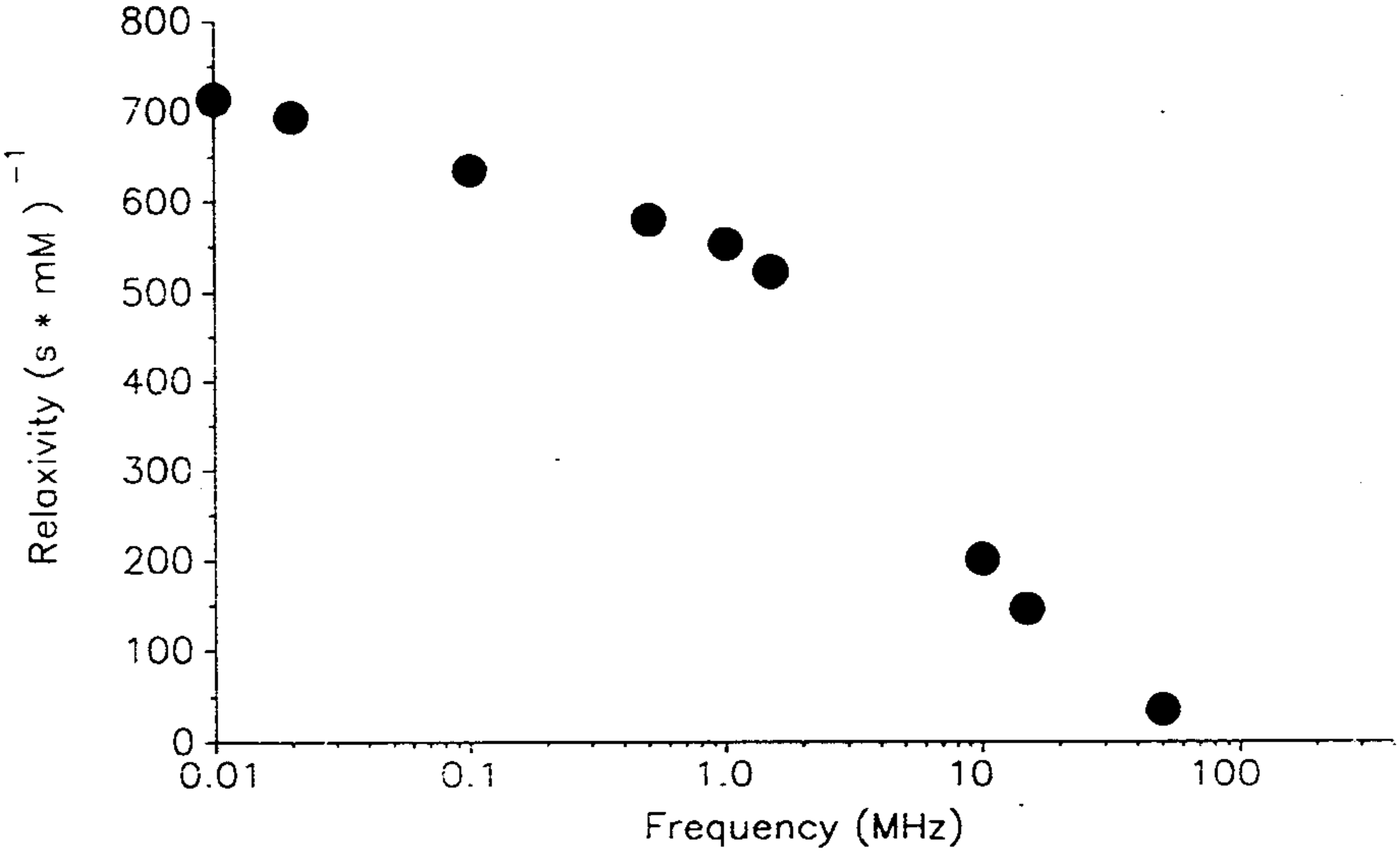

Magnetite Coated Particles
(Polysciences 19633 ; 0.039mM Fe)
20C
Relaxivity (s * mM)$^{-1}$
800
700
600
500
400
300
200
100
0
0.01
0.1
1.0
10
100
Frequency (MHz)

L 420


Magnetite Coated Particles
(Polysciences 19633 ; 0.039mM Fe)
25C
Relaxivity (s * mM)^-1
800
700
600
500
400
300
200
100
0
0.01
0.1
1.0
10
100
Frequency (MHz)

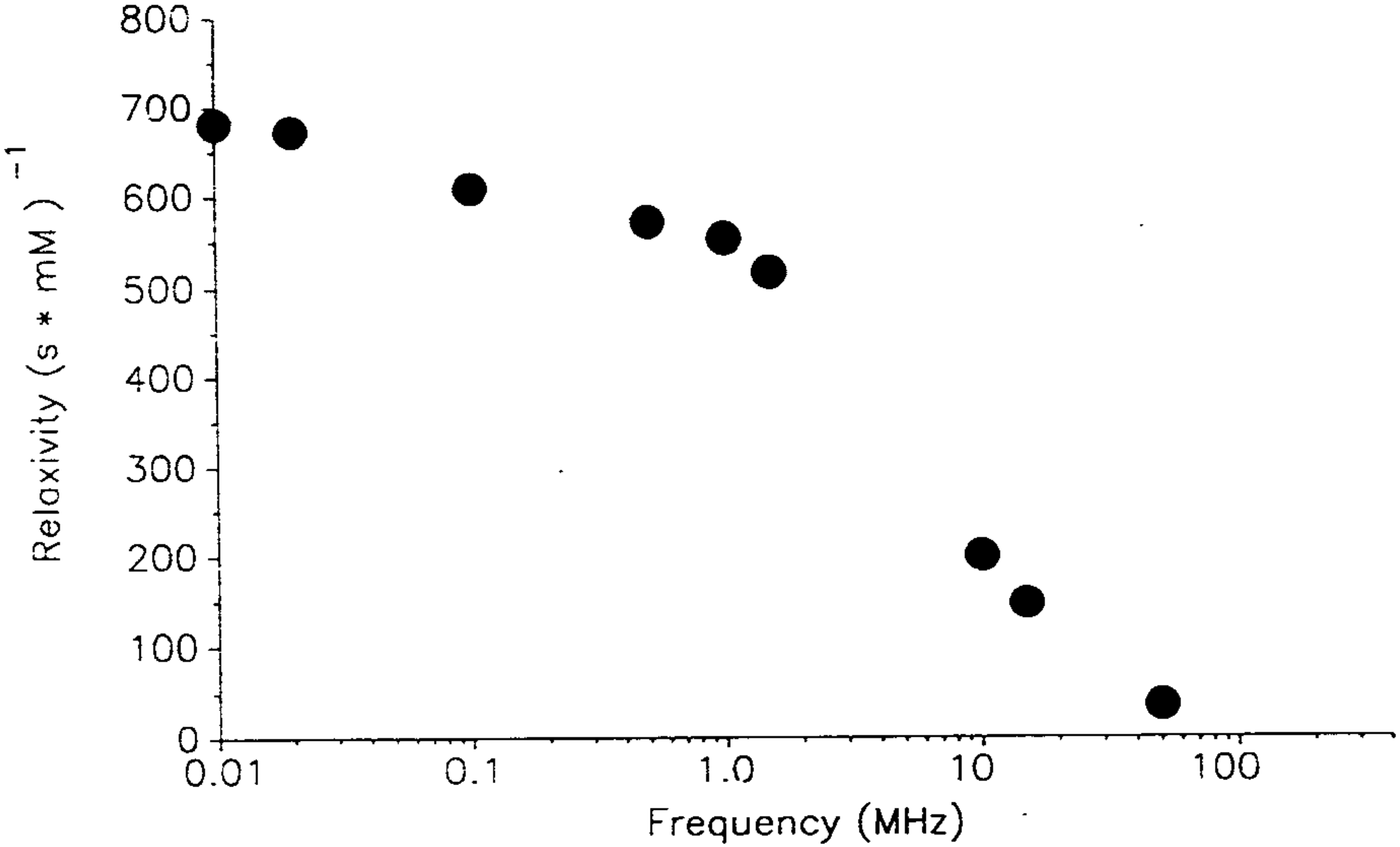
L425

Magnetite Coated Particles
(Polysciences 19633 ; 0.039mM Fe)
30C

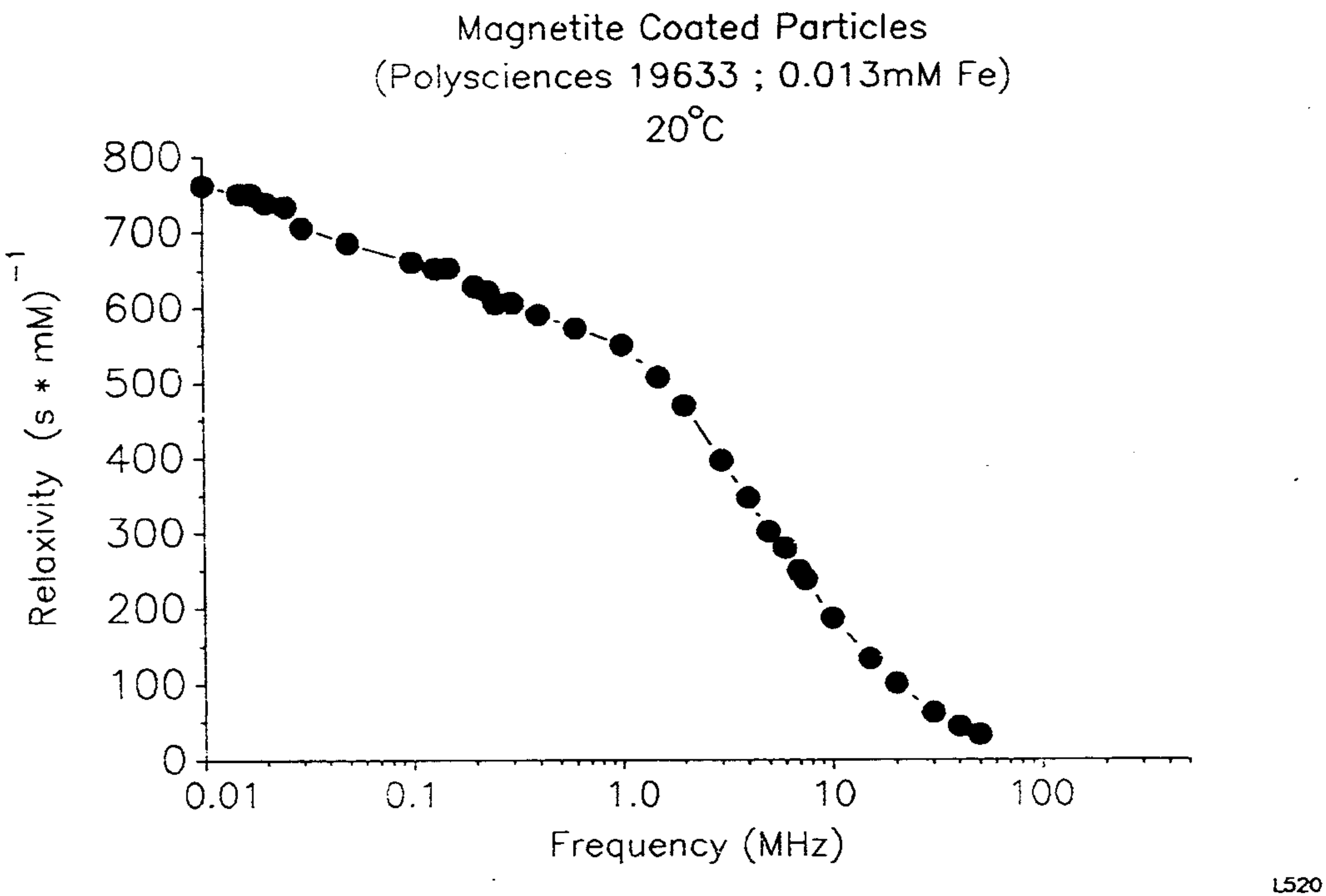


L430

Magnetite Coated Particles
(Polysciences 19633 ; 0.039mM Fe)
35C



L435


Magnetite Coated Particles
(Polysciences 19633 ; 0.013mM Fe)
20°C
Relaxivity (s * mM)$^{-1}$
800
700
600
500
400
300
200
100
0
0.01
0.1
1.0
10
100
Frequency (MHz)
L520

A120A

Relaxation measurements
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Material: AMI 25 lot # : B032101
Descript.:superparamag. paricles/polymeric matrix
Temp. : 20C Date: Oct. 25,88
(Fe)= 10.86 u-g/ml = 0.1945 mM

Frequency	Field	1/T1	1/T1 -1/T1 (H2O)	R1	Comments	1/T2	1/T2 -1/T2 (H2O)	R2	1/T1 (H2O)	1/T2 (H2O)
MHz	Gauss	1/s	1/s	1/(s*mM)		1/s	1/s	1/(s*mM)	1/s	1/s
0.02	4.7	2.95	2.478	12.74	Relaxometer #101		0	0.00	0.472	
0.05	11.75	2.93	2.459	12.65			0	0.00	0.471	
0.1	23.5	2.96	2.49	12.80			0	0.00	0.47	
0.2	47	3.05	2.585	13.29			0	0.00	0.465	
0.3	70.5	3.13	2.667	13.71			0	0.00	0.463	
0.5	117.5	3.42	2.954	15.19			0	0.00	0.466	
1	235	4.13	3.67	18.87			0	0.00	0.46	
2	470	5.24	4.791	24.64			0	0.00	0.449	
3	705	5.8	5.356	27.54			0	0.00	0.444	
4	940	6.16	5.719	29.41			0	0.00	0.441	
5	1175	6.27	5.828	29.97			0	0.00	0.442	
6	1410	6.35	5.91	30.39			0	0.00	0.44	
7	1645	6.26	5.827	29.97			0	0.00	0.433	
8	1880	6.21	5.774	29.69			0	0.00	0.436	
10	2350	6.08	5.647	29.04			0	0.00	0.433	
15	3525	5.43	5.01	25.76			0	0.00	0.42	
20	4700	4.87	4.456	22.91			0	0.00	0.414	
30	7050	3.88	3.479	17.89			0	0.00	0.401	
40	9400	3.25	2.856	14.69			0	0.00	0.394	
50	11750	2.82	2.431	12.50			0	0.00	0.389	
200	47000	0.893	0.57	2.93	23C	25.4	25.03	128.72	0.323	0.37

A220A

Relaxation measurements
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Material: AMI 25 lot # : 8032101
Descript.:superparamag. paricles/polymeric matrix
Temp. : 20C Date: Oct. 25,88
[Fe]= 7.28 u-g/ml = 0.1304 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (H2O) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (H2O) 1/s	R2 1/(s*mM)	1/T1 (H2O) 1/s	1/T2 (H2O) 1/s
0.02	4.7	2.13	1.658	12.72	Relaxometer #102		0	0.00	0.472	
0.05	11.75	2.12	1.649	12.65			0	0.00	0.471	
0.1	23.5	2.16	1.69	12.96			0	0.00	0.47	
0.2	47	2.2	1.735	13.31			0	0.00	0.465	
0.3	70.5	2.27	1.807	13.86			0	0.00	0.463	
0.5	117.5	2.43	1.964	15.07			0	0.00	0.466	
1	235	2.93	2.47	18.95			0	0.00	0.46	
2	470	3.68	3.231	24.79			0	0.00	0.449	
3	705	4.11	3.666	28.12			0	0.00	0.444	
4	940	4.29	3.849	29.53			0	0.00	0.441	
5	1175	4.39	3.948	30.29			0	0.00	0.442	
6	1410	4.41	3.97	30.46			0	0.00	0.44	
7	1645	4.39	3.957	30.36			0	0.00	0.433	
8	1880	4.35	3.914	30.03			0	0.00	0.436	
10	2350	4.2	3.767	28.90			0	0.00	0.433	
15	3525	3.84	3.42	26.24			0	0.00	0.42	
20	4700	3.47	3.056	23.44			0	0.00	0.414	
30	7050	2.78	2.379	18.25			0	0.00	0.401	
40	9400	2.34	1.946	14.93			0	0.00	0.394	
50	11750	2.05	1.661	12.74			0	0.00	0.389	
200	47000	0.683	0.36	2.76	23C	20.4	20.03	153.66	0.323	0.37

A320A

Relaxation measurements

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Material: AMI 25 lot # : 8032101
Descript.:superparamag. particles/polymeric matrix
Temp. : 20C Date: Oct. 29,88
[Fe]= 3.64 u-g/ml = 0.0652 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (H2O) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (H2O) 1/s	R2 1/(s*mM)	1/T1 (H2O) 1/s	1/T2 (H2O) 1/s
0.02	4.7	1.48	1.008	15.47	Relaxometer #103		0	0.00	0.472	
0.05	11.75	1.47	0.999	15.3[illegible]			0	0.00	0.471	
0.1	23.5	1.49	1.02	15.65			0	0.00	0.47	
0.2	47	1.57	1.105	16.95			0	0.00	0.465	
0.3	70.5	1.54	1.077	16.52			0	0.00	0.463	
0.5	117.5	1.71	1.244	19.09			0	0.00	0.466	
1	233	1.91	1.45	22.25			0	0.00	0.46	
2	470	2.25	1.801	27.63			0	0.00	0.449	
3	705	2.42	1.976	30.32			0	0.00	0.444	
5	1175	2.55	2.108	32.34			0	0.00	0.442	
6	1410	2.53	2.09	32.07			0	0.00	0.44	
7	1645	2.6	2.167	33.25			0	0.00	0.433	
8	1880	2.52	2.084	31.97			0	0.00	0.436	
10	2350	2.54	2.107	32.33			0	0.00	0.433	
15	3525	2.18	1.76	27.00			0	0.00	0.42	
20	4700	2.05	1.636	25.10			0	0.00	0.414	
30	7050	1.33	0.929	14.25			0	0.00	0.401	
40	9400	1.11	0.716	10.99			0	0.00	0.394	
50	11750	1	0.611	9.37			0	0.00	0.389	
200	47000	0.493	0.17	2.61	23C	13.4	13.03	197.91	0.323	0.37

A237A

Relaxation measurements
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Material: AMI 25 lot # : 8032101
Descript.:superparamag. particles/polymeric matrix
Temp. : 36.6C Date: Dec. 15,88
(Fe)= 7.28 u-g/ml = 0.1304 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (H2O) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (H2O) 1/s	R2 1/(s*mM)	1/T1 (H2O) 1/s	1/T2 (H2O) 1/s
0.02	4.7	1.621	1.305	10.01	Relaxometer #102		0	0.00	0.316	
0.1	23.5	1.629	1.316	10.10			0	0.00	0.313	
0.2	47	1.663	1.353	10.38			0	0.00	0.31	
0.3	70.5	1.703	1.395	10.70			0	0.00	0.308	
0.5	117.5	1.833	1.528	11.72			0	0.00	0.305	
1	235	2.173	1.872	14.36			0	0.00	0.301	
2	470	2.707	2.411	18.50			0	0.00	0.296	
3	705	2.998	2.7015	20.72			0	0.00		
4	940	3.205	2.908	22.31			0	0.00	0.297	
5	1175	3.293	3.001	23.02			0	0.00	0.292	
6	1410	3.344	3.048	23.38			0	0.00	0.296	
7	1645	3.347	3.052	23.41			0	0.00	0.295	
8	1880	3.344	3.046	23.37			0	0.00	0.298	
10	2350	3.288	3.001	23.02	PC-10	8.63	7.716	59.19	0.287	0.914
15	3525	3.093	2.809	21.55			0	0.00		
20	4700	2.796	2.515	19.29	PC-20	11.88	10.741	82.40	0.281	1.139
30	7050	2.379	2.107	16.16			0	0.00	0.272	
40	9400	2.04	1.772	13.59			0	0.00	0.268	
50	11750	1.796	1.531	11.74			0	0.00	0.265	

B205

Relaxation measurements
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Material: Polysciences #19632 lot # : 81159
Descript.:Magnetite particles coated w/ polymer
Temp. : 5C Date: March 14,89
[Fe]= 7.28 u-g/ml = 0.1304 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (H2O) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (H2O) 1/s	R2 1/(s*mM)	1/T1 (H2O) 1/s	1/T2 (H2O) 1/s
0.02	4.7	43.674	43.202	331.42	Relaxometer # 13		0	0.00	0.472	
0.03	7.05	42.913	42.442	325.58			0	0.00		
0.04	9.4	42.624	42.153	323.37			0	0.00	0.471	
0.05	11.75	41.112	40.641	311.77			0	0.00	0.471	
0.06	14.1	40.858	40.387	309.82			0	0.00	0.471	
0.08	18.8	40.692	40.222	308.55			0	0.00	0.47	
0.1	23.5	40.017	39.547	303.38			0	0.00	0.47	
0.15	35.25	38.846	38.381	294.43			0	0.00	0.465	
0.2	47	38.254	37.789	289.89			0	0.00	0.465	
0.3	70.5	37.089	36.626	280.97			0	0.00	0.463	
0.4	94	37.504	37.041	284.15			0	0.00	0.463	
0.6	141	36.546	36.084	276.81			0	0.00		
0.8	193	35.226	34.765	266.69			0	0.00	0.461	
1	235	33.864	33.404	256.25			0	0.00	0.46	
1.5	352.5	32.871	32.416	249.67			0	0.00	0.455	
2	470	30.459	30.008	230.20			0	0.00		
3	705	26.159	25.715	197.27			0	0.00	0.444	
4	940	23.138	22.698	174.12			0	0.00	0.44	
6	1410	18.739	18.302	140.40			0	0.00		
8	1830	15.739	15.306	117.42			0	0.00	0.433	
10	2350	13.273	12.840	98.50			0	0.00	0.433	
15	3525	9.468	9.045	69.33			0	0.00		
20	4700	7.137	6.723	51.57			0	0.00	0.414	
30	7050	4.708	4.307	33.04			0	0.00	0.401	
40	9400	3.435	3.041	23.33			0	0.00	0.394	
50	11750	2.724	2.335	17.91			0	0.00	0.399	

б 2/3

Relaxation measurements
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Material: Polysciences #19632   lot # : 81159
Descript.:Magnetite particles coated w/ polymer
Temp. : 13C   Date: March 14,89
[Fe]=   7.28 u-g/ml =   0.1304 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (H2O) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (H2O) 1/s	R2 1/(s*mM)	1/T1 (H2O) 1/s	1/T2 (H2O) 1/s
0.02	4.7	41.792	41.320	316.98	Relaxometer # 13		0	0.00	0.472	
0.03	7.05	41.331	40.860	313.45			0	0.00		
0.04	9.4	41.57	41.099	315.28			0	0.00	0.471	
0.05	11.75	40.031	39.560	303.48			0	0.00	0.471	
0.06	14.1	40.572	40.101	307.63			0	0.00	0.471	
0.08	18.8	39.479	39.009	299.25			0	0.00	0.47	
0.1	23.5	39.823	39.353	301.89			0	0.00	0.47	
0.15	35.25	36.954	36.489	279.92			0	0.00	0.465	
0.2	47	37.653	37.189	285.28			0	0.00	0.465	
0.3	70.5	36.646	36.195	277.59			0	0.00	0.453	
0.4	94	36.852	36.389	279.15			0	0.00	0.463	
0.6	141	36.934	36.472	279.79			0	0.00		
0.8	198	34.865	34.404	263.92			0	0.00	0.451	
1	235	34.533	34.073	261.38			0	0.00	0.46'	
1.5	352.5	32.706	32.251	247.41			0	0.00	0.455	
2	470	30.594	30.143	231.23			0	0.00		
3	705	26.84	26.396	202.49			0	0.00	0.444	
4	940	23.407	22.967	176.19			0	0.00	0.44	
6	1410	19.483	19.047	146.11			0	0.00		
8	1880	16.102	15.669	120.20			0	0.00	0.433	
10	2350	14.119	13.686	104.99			0	0.00	0.433	
15	3525	10.165	9.702	74.42			0	0.00		
20	4700	7.707	7.293	55.95			0	0.00	0.414	
30	7050	4.945	4.544	34.86			0	0.00	0.401	
40	9400	3.695	3.301	25.32			0	0.00	0.394	
50	11750	2.739	2.350	18.03			0	0.00	0.359	

B220

Relaxation measurements
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Material: Polysciences #19632   lot # : 81159
Descript.:Magnetite particles coated w/ polymer
Temp. : 20C   Date: Nov. 4,88
[Fe]=   7.28 u-g/ml =   0.1304 mM

Frequency	Field	1/T1	1/T1 -1/T1 (H2O)	R1	Comments	1/T2	1/T2 -1/T2 (H2O)	R2	1/T1 (H2O)	1/T2 (H2O)
MHz	Gauss	1/s	1/s	1/(s*mM)		1/s	1/s	1/(s*mM)	1/s	1/s
0.01	2.35	42.423	41.951	321.62	Avg. of Relaxometer #107 & #13		0	0.00	0.472	
0.013	3.055	41.21	40.738	312.51			0	0.00	0.472	
0.015	3.525	41.571	41.099	315.28			0	0.00	0.472	
0.017	3.995	41.54	41.068	315.04			0	0.00	0.472	
0.02	4.7	40.816	40.344	309.49			0	0.00	0.472	
0.03	7.05	40.036	39.564333	303.51			0	0.00		
0.05	11.75	39.24	38.769	297.41			0	0.00	0.471	
0.07	16.45	38.855	38.3844	294.45			0	0.00		
0.1	23.5	37.896	37.426	287.11			0	0.00	0.47	
0.13	30.55	36.73	36.263	278.18			0	0.00		
0.15	35.25	36.8	36.335	278.74			0	0.00	0.465	
0.2	47	36.71	36.245	278.05			0	0.00	0.465	
0.23	54.05	36.14	35.677	273.69			0	0.00	0.463	
0.25	58.75	36.472	36.009	276.24			0	0.00		
0.3	70.5	36.026	35.563	272.81			0	0.00	0.463	
0.4	94	35.942	35.479	272.17			0	0.00	0.463	
0.6	141	35.542	35.08	269.11			0	0.00		
1	235	35.12	34.66	265.89			0	0.00	0.46	
3	705	27.86	27.416	210.32			0	0.00	0.444	
7	1645	18.37	17.937	137.60			0	0.00	0.433	
10	2350	14.64	14.207	108.99			0	0.00	0.433	
20	4700	8.263	7.849	60.21			0	0.00	0.414	
30	7050	5.346	4.945	37.93			0	0.00	0.401	
40	9400	3.[illegible]89	3.595	27.58			0	0.00	0.394	
50	11750	[illegible].08	2.6[illegible]1	20.64			0	0.00	0.399	
200	47000	[illegible].71	0.397	2.97	230	100	99.63	764.29	0.323	0.3[illegible]

B237

Relaxation measurements
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Material: Polysciences #19632   lot # : 81159
Descript.:Magnetite particles coated w/ a polymer
Temp. : 37C   Date: Dec. 6,88
[Fe]=   7.28 u-g/ml =   0.1304 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (H2O) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (H2O) 1/s	R2 1/(s*mM)	1/T1 (H2O) 1/s	1/T2 (H2O) 1/s
0.01	2.35	33.92	33.605	257.77	Relaxometer #13		0	0.00	0.315	
0.015	3.525	34.951	34.6355	265.70			0	0.00		
0.02	4.7	34.256	33.94	260.36			0	0.00	0.316	
0.03	7.05	34.15	33.835333	259.56			0	0.00		
0.05	11.75	33.536	33.224	254.87			0	0.00	0.312	
0.07	16.45	32.796	32.484	249.19			0	0.00	0.312	
0.09	21.15	32.152	31.84	244.25			0	0.00	0.312	
0.1	23.5	32.309	31.996	245.45			0	0.00	0.313	
0.2	47	31.867	31.554	242.06			0	0.00	0.313	
0.25	58.75	32.105	31.792	243.89			0	0.00	0.313	
0.3	70.5	32.06	31.747	243.54			0	0.00	0.313	
0.4	94	22.099	31.786	243.84			0	0.00	0.313	
0.5	117.5	31.454	31.149	238.95			0	0.00	0.305	
0.6	141	31.953	31.648	242.78			0	0.00		
0.7	164.5	32.384	32.079	246.09			0	0.00	0.305	
1	235	31.591	31.29	240.03			0	0.00	0.301	
3	705	26.639	26.343	202.09			0	0.00	0.296	
5	1175	21.683	21.391	164.10			0	0.00	0.292	
10	2350	14.766	14.479	111.07	T2 on FC-10	49.1	47.186	361.96	0.287	0.914
20	4700	8.687	8.406	64.48			-1.139	-8.74	0.281	1.139
30	7050	5.694	5.422	41.59			0	0.00	0.272	
40	9400	4.266	3.992	30.67			0	0.00	0.268	
50	11750	3.363	3.098	23.77			0	0.00	0.265	

BS20.GAK

Relaxation measurements
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Materials Polysciences #19632   lot # : 81159
Descript.:Magnetite particles coated w/ a polymer
Temp. : 20C   Date: Dec. 8,88
[Fe]=   0.728 u-g/ml =   0.0130 mM

Frequency	Field	1/T1	1/T1 -1/T1 (H2O)	R1	Comments	1/T2	1/T2 -1/T2 (H2O)	R2	1/T1 (H2O)	1/T2 (H2O)
MHz	Gauss	1/s	1/s	1/(s*mM)		1/s	1/s	1/(s*mM)	1/s	1/s
0.01	2.35	4.693	4.221	323.81	Relaxometer #14 (I. S.)		0	0.00	0.472	
0.02	4.7	4.637	4.165	319.51			0	0.00	0.472	
0.03	7.05	4.557	4.086	313.45			0	0.00	0.471	
0.04	9.4	4.49	4.019	308.31			0	0.00	0.471	
0.05	11.75	4.478	4.007	307.39			0	0.00	0.471	
0.06	14.1	4.432	3.962	303.94			0	0.00	0.47	
0.07	16.45	4.421	3.951	303.09			0	0.00	0.47	
0.08	18.8	4.388	3.918	300.56			0	0.00	0.47	
0.09	21.15	4.382	3.912	300.10			0	0.00	0.47	
0.1	23.5	4.343	3.873	297.11			0	0.00	0.47	
0.2	47	4.239	3.774	289.51			0	0.00	0.465	
0.3	70.5	4.177	3.714	284.91			0	0.00	0.463	
0.4	94	4.134	3.6695	281.50			0	0.00		
0.5	117.5	4.101	3.635	278.85			0	0.00	0.466	
0.6	141	4.079	3.614	277.24			0	0.00	0.465	
0.7	164.5	4.067	3.603	276.40			0	0.00	0.464	
0.8	188	4.015	3.552	272.48			0	0.00	0.463	
0.9	211.5	3.99	3.529	270.72			0	0.00	0.461	
1	235	3.969	3.509	269.19			0	0.00	0.46	
2	470	3.567	3.118	239.19			0	0.00	0.449	
3	705	3.184	2.74	210.19			0	0.00	0.444	
5	1175	2.605	2.163	165.93			0	0.00	0.442	
10	2350	1.857	1.424	109.24			0	0.00	0.433	
20	4700	1.213	0.799	61.29			0	0.00	0.414	
30	7050	0.902	0.501	38.43			0	0.00	0.401	
40	9400	0.76	0.366	28.08			0	0.00	0.394	
50	11750	0.849	0.46	35.29	this point should be remeas.		0	0.00	0.389	
200	47000	0.376	0.053	4.07	23C	9.09	8.72	668.94	0.323	0.37

BS20

Relaxation measurements
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Material: Polysciences #19632   lot # : 81159
Descript.:Magnetite particles coated w/ a polymer
Temp. : 20C   Date: Dec. 13,88
[Fe]=   0.724 u-g/ml =   0.0130 mM

Frequency	Field	1/T1	1/T1 -1/T1 (H2O)	R1	Comments	1/T2	1/T2 -1/T2 (H2O)	R2	1/T1 (H2O)	1/T2 (H2O)
MHz	Gauss	1/s	1/s	1/(s*mM)		1/s	1/s	1/(s*mM)	1/s	1/s
0.01	2.35	3.991	3.519	271.44	Relaxometer #14 ([illegible])		0	0.00	0.472	
0.02	4.7	3.997	3.525	271.91			0	0.00	0.472	
0.03	7.05	3.887	3.416	263.50			0	0.00	0.471	
0.04	9.4	3.819	3.348	258.25			0	0.00	0.471	
0.05	11.75	3.788	3.317	255.86			0	0.00	0.471	
0.06	14.1	3.887	3.417	263.58			0	0.00	0.47	
0.07	16.45	3.859	3.389	261.42			0	0.00	0.47	
0.08	18.8	3.852	3.382	260.88			0	0.00	0.47	
0.09	21.15	3.824	3.354	258.72			0	0.00	0.47	
0.1	23.5	3.802	3.332	257.02			0	0.00	0.47	
0.2	47	3.652	3.187	245.83			0	0.00	0.465	
0.3	70.5	3.654	3.191	246.14			0	0.00	0.463	
0.4	94	3.612	3.1475	242.79			0	0.00		
0.5	117.5	3.582	3.116	240.36			0	0.00	0.466	
0.6	141	3.531	3.066	236.50			0	0.00	0.465	
0.7	164.5	3.511	3.047	235.04			0	0.00	0.464	
0.8	188	3.369	2.906	224.16			0	0.00	0.463	
0.9	211.5	3.351	2.89	222.93			0	0.00	0.461	
1	235	3.312	2.852	219.99			0	0.00	0.46	
2	470	2.984	2.535	195.54			0	0.00	0.449	
3	705	2.729	2.235	176.26			0	0.00	0.444	
5	1175	2.247	1.805	139.23			0	0.00	0.442	
10	2350	1.596	1.163	89.71			0	0.00	0.433	
20	4700	1.053	0.639	49.29			0	0.00	0.414	
30	7050	0.813	0.412	31.78			0	0.00	0.401	
40	9400	0.686	0.292	22.52			0	0.00	0.394	
50	11750	0.612	0.223	17.20			0	0.00	0.389	
200	47000	0.376	0.053	4.09	23C	9.09	8.72	672.63	0.323	0.37

B537

Relaxation measurements
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Material: Polysciences #19632 lot # : 81159
Descript.:Magnetite particles coated w/ a polymer
Temp. : 37.2C Date: Dec. 8,88
[Fe]= 0.728 u-g/ml = 0.0130 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (H2O) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (H2O) 1/s	R2 1/(s*mM)	1/T1 (H2O) 1/s	1/T2 (H2O) 1/s
0.01	2.35	3.853	3.538	271.41	Relaxometer #14		0	0.00	0.315	
0.02	4.7	3.814	3.498	268.34			0	0.00	0.316	
0.03	7.05	3.761	3.447	264.43			0	0.00	0.314	
0.04	9.4	3.734	3.421	262.43			0	0.00	0.313	
0.05	11.75	3.713	3.401	260.90			0	0.00	0.312	
0.06	14.1	3.657	3.345	256.60			0	0.00	0.312	
0.08	18.8	3.642	3.33	255.45			0	0.00	0.312	
0.1	23.5	3.604	3.291	252.46			0	0.00	0.313	
0.2	47	3.532	3.222	247.17			0	0.00	0.31	
0.3	70.5	3.518	3.21	246.25			0	0.00	0.308	
0.4	94	3.519	3.213	246.48			0	0.00	0.306	
0.6	141	3.508	3.203	245.71			0	0.00	0.305	
0.8	188	3.532	3.227	247.55			0	0.00	0.305	
1	235	3.494	3.193	244.94			0	0.00	0.301	
1.5	352.5	3.769	3.4695	266.16			0	0.00		
2	470	3.205	2.909	223.16			0	0.00	0.296	
3	705	2.908	2.611	200.30			0	0.00	0.297	
5	1175	2.418	2.126	163.09			0	0.00	0.292	
10	2350	1.696	1.409	108.09	T2 on PC-10	7.59	6.666	511.37	0.287	0.914
20	4700	1.082	0.801	61.45			-1.139	-87.38	0.281	1.139
30	7050	0.813	0.541	41.50			0	0.00	0.272	
40	9400	0.666	0.398	30.53			0	0.00	0.268	
50	11750	0.699	0.434	33.29			0	0.00	0.265	

Relaxation measurements
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Material: Polysciences #19631 lot # : 81157
Descript.:Magnetite particles coated w/ a polymer
Temp. : 19.5C Date: Dec. 9,88
[Fe]= 7.28 u-g/ml = 0.1304 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (H2O) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (H2O) 1/s	R2 1/(s*mM)	1/T1 (H2O) 1/s	1/T2 (H2O) 1/s
0.01	2.35	39.605	39.133	300.20	Relaxometer #15		0	0.00	0.472	
0.02	4.7	38.487	38.015	291.62			0	0.00	0.472	
0.03	7.05	37.616	37.144	284.94			0	0.00	0.472	
0.04	9.4	36.638	36.166	277.44			0	0.00	0.472	
0.05	11.75	36.887	36.416	279.36			0	0.00	0.471	
0.06	14.1	36.393	35.922	275.57			0	0.00	0.471	
0.08	18.8	35.122	34.651	265.82			0	0.00	0.471	
0.1	23.5	35.356	34.886	267.62			0	0.00	0.47	
0.2	47	33.255	32.79	251.54			0	0.00	0.465	
0.3	70.5	32.633	32.17	246.79			0	0.00	0.463	
0.4	94	31.408	30.945	237.39			0	0.00	0.463	
0.6	141	30.703	30.241	231.99			0	0.00	0.462	
0.8	188	29.915	29.4545	225.95			0	0.00		
1	235	28.461	28.001	214.80			0	0.00	0.46	
2	470	24.065	23.616	181.17			0	0.00	0.449	
3	705	20.391	19.947	153.02			0	0.00	0.444	
5	1175	15.145	14.703	112.79			0	0.00	0.442	
10	2350	9.152	8.719	66.89			0	0.00	0.433	
20	4700	4.854	4.44	34.06			0	0.00	0.414	
30	7050	3.179	2.778	21.31			0	0.00	0.401	
40	9400	2.328	1.934	14.84			0	0.00	0.394	
50	11750	1.818	1.429	10.96			0	0.00	0.389	
200	47000	0.514	0.191	1.47	SIS 200/330 @ 23C	111	110.63	849.67	0.323	0.37

C237

Relaxation measurements
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Material: POlysciences #19631   lot # : 81157
Descript.:Magnetite particles coated w/ a polymer
Temp. : 37C   Date: Dec. 9,88
(Fe)=   7.28 u-g/ml =   0.1304 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (H2O) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (H2O) 1/s	R2 1/(s*mM)	1/T1 (H2O) 1/s	1/T2 (H2O) 1/s
0.01	2.35	33.425	33.11	254.00	Relaxometer #15		0	0.00	0.315	
0.02	4.7	32.845	32.529	249.54			0	0.00	0.316	
0.03	7.05	32.494	32.179	246.85			0	0.00	0.315	
0.04	9.4	32.129	31.814	244.05			0	0.00	0.315	
0.05	11.75	31.773	31.461	241.35			0	0.00	0.312	
0.06	14.1	31.514	31.202	239.36			0	0.00	0.312	
0.08	18.8	30.345	30.033	230.39			0	0.00	0.312	
0.1	23.5	30.903	30.59	234.66			0	0.00	0.313	
0.15	35.25	31.147	30.834	236.54			0	0.00	0.313	
0.2	47	30.148	29.835	228.87			0	0.00	0.313	
0.3	70.5	29.548	29.236789	224.28			0	0.00		
0.4	94	29.397	29.092	223.17			0	0.00	0.305	
0.6	141	29.292	28.987	222.37			0	0.00	0.305	
0.8	188	28.521	28.217285	216.46			0	0.00		
1	235	28.1	27.799	213.25			0	0.00	0.301	
2	470	24.215	23.919	183.49			0	0.00	0.296	
3	705	20.165	19.868	152.41			0	0.00	0.297	
5	1175	15.564	15.272	117.16			0	0.00	0.292	
10	2350	9.583	9.296	71.31	T2 on PC-10	72	71.086	545.32	0.287	0.914
20	4700	5.093	4.812	36.91			-1.139	-9.74	0.281	1.139
30	7050	3.338	3.066	23.52			0	0.00	0.272	
50	11750	1.967	1.702	13.06			0	0.00	0.255	

Relaxation measurements
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Material: Polysciences #19631 lot # : 81157
Descript.:Magnetite particles coated w/ a polymer
Temp. : 19.8C Date: Dec. 9,88
[Fe]= 0.728 u-g/ml = 0.0130 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (H2O) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (H2O) 1/s	R2 1/(s*mM)	1/T1 (H2O) 1/s	1/T2 (H2O) 1/s
0.01	2.35	4.449	3.976	305.01	Relaxometer #16		0	0.00	0.472	
0.02	4.7	4.4	3.928	301.33			0	0.00	0.472	
0.03	7.05	4.311	3.839	294.50			0	0.00	0.472	
0.04	9.4	4.216	3.744	287.21			0	0.00	0.472	
0.05	11.75	4.216	3.745	287.29			0	0.00	0.471	
0.06	14.1	4.168	3.697	283.61			0	0.00	0.471	
0.08	18.8	4.046	3.575	274.25			0	0.00	0.471	
0.1	23.5	4.018	3.548	272.18			0	0.00	0.47	
0.15	35.25	3.925	3.4575	265.23			0	0.00		
0.2	47	3.865	3.4	260.82			0	0.00	0.465	
0.3	70.5	3.758	3.295	252.77			0	0.00	0.463	
0.4	94	3.655	3.191	244.79			0	0.00		
0.6	141	3.554	3.088	236.89			0	0.00	0.466	
0.8	188	3.438	2.975	228.22			0	0.00		
1	235	3.339	2.879	220.86			0	0.00	0.46	
1.5	352.5	3.039	2.5845	198.26			0	0.00		
2	470	2.79	2.341	179.58			0	0.00	0.449	
3	705	2.439	1.995	153.04			0	0.00	0.444	
5	1175	1.91	1.468	112.61			0	0.00	0.442	
10	2350	1.293	0.86	65.97			0	0.00	0.433	
15	3525	1.026	0.606	46.49			0	0.00	0.42	
19	4465	0.89	0.4748	36.42			0	0.00		
20	4700	0.841	0.427	32.76			0	0.00	0.414	
21	4935	0.848	0.434	33.29			0	0.00	0.414	
26	6110	0.735	0.329125	25.25			0	0.00		
29	6815	0.694	0.293	22.48			0	0.00	0.401	
30	7050	0.681	0.28	21.48			0	0.00	0.401	
34	7990	0.639	0.239	18.33			0	0.00	0.4	
36	8460	0.621	0.2235	17.15			0	0.00		
38	8930	0.605	0.21	16.11			0	0.00	0.395	
39	9165	0.601	0.207	15.88			0	0.00	0.394	
44	10340	0.571	0.178	13.65			0	0.00	0.393	
46	10810	0.556	0.1645	12.62			0	0.00		
48	11280	0.545	0.156	11.97			0	0.00	0.39	
49.5	11632.5	0.54	0.151	11.58			0	0.00	0.389	
50	11750	0.541	0.152	11.66			0	0.00	0.389	
200	47000	0.326	0.003	0.23	SIS 200/330 @ 23C	9.9	9.53	731.07	0.323	0.37

C537

Relaxation measurements
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Material: Polysciences #19631   lot # : 81157
Descript.:Magnetite coated w/ a polymer
Temp. : 37.3C   Date: Dec. 9,88
[Fe]= 0.728 u-g/ml = 0.0130 mM

Frequency (MHz)	Field (Gauss)	1/T1 (1/s)	1/T1 -1/T1 (H2O) (1/s)	R1 (1/(s*mM))	Comments	1/T2 (1/s)	1/T2 -1/T2 (H2O) (1/s)	R2 (1/(s*mM))	1/T1 (H2O) (1/s)	1/T2 (H2O) (1/s)
0.01	2.35	3.823	3.508	269.11	Relaxometer #16		0	0.00	0.315	
0.02	4.7	3.748	3.432	263.28			0	0.00	0.316	
0.03	7.05	3.695	3.38	259.29			0	0.00	0.315	
0.04	9.4	3.674	3.361	257.83			0	0.00	0.313	
0.05	11.75	3.588	3.276	251.31			0	0.00	0.312	
0.06	14.1	3.586	3.274	251.16			0	0.00	0.312	
0.00	18.8	3.501	3.1[illegible]9	244.64			0	0.00	0.312	
0.1	23.5	3.521	3.208	246.10			0	0.00	0.313	
0.15	35.25	3.441	3.128	239.96			0	0.00	0.313	
0.2	47	3.414	3.104	238.12			0	0.00	0.31	
0.3	70.5	3.373	3.064	235.05			0	0.00	0.309	
0.4	94	3.348	3.041	233.28			0	0.00	0.307	
0.6	141	3.299	2.994	229.68			0	0.00	0.305	
0.8	188	3.222	2.917	223.77			0	0.00	0.305	
1	235	3.152	2.851	218.71			0	0.00	0.301	
2	470	2.744	2.448	187.79			0	0.00	0.296	
3	705	2.321	2.024	155.27			0	0.00	0.297	
5	1175	1.819	1.527	117.14			0	0.00	0.292	
10	2350	1.221	0.934	71.65	T2 on FC-10	9.3	8.386	643.31	0.287	0.914
20	4700	0.846	0.565	43.34			-1.139	-87.38	0.281	1.139
30	7050	0.817	0.545	41.81			0	0.00	0.272	
50	11750	1.128	0.853	66.20	??? (big error)		0	0.00	0.265	

D220

Relaxation measurements
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Material: Polysciences #19131   lot # : 22307
Descript.:0.047micron (s.d. 0.003) superparamag. particles/polystyrene matrix in 0.5% agar gel
Temp. : 20C   Date: Feb. 7,89
[Fe]=   7.28 u-g/ml =   0.1304 mM

Frequency	Field	1/T1	1/T1 -1/T1 (agar)	R1	Comments	1/T2	1/T2 -1/T2 (agar)	R2	1/T1 (agar)	1/T2 (agar)
MHz	Gauss	1/s	1/s	1/(s*mM)		1/s	1/s	1/(s*mM)	1/s	1/s
0.02	4.7	9.421	5.84	44.81	Relaxometer # 3c		0.00	0.00	3.58	
0.03	7.05	8.972	5.79	44.41			0.00	0.00		
0.04	9.4	8.587	5.80	44.52			0.00	0.00	2.785	
0.06	14.1	8.061	5.91	45.35			0.00	0.00	2.15	
0.08	18.8	7.642	5.78	44.33			0.00	0.00	1.863	
0.1	23.5	7.489	5.90	45.27			0.00	0.00	1.588	
0.15	35.25	7.157	5.90	45.25			0.00	0.00	1.269	
0.2	47	7.089	5.98	45.91			0.00	0.00	1.105	
0.3	70.5	7.196	6.26	48.01			0.00	0.00	0.937	
0.4	94	7.458	6.60	50.62			0.00	0.00	0.86	
0.6	141	7.79	7.02	53.81			0.00	0.00	0.775	
0.8	188	8.251	7.52	57.70			0.00	0.00	0.73	
1	235	8.477	7.77	59.64			0.00	0.00	0.705	
1.5	352.5	8.962	8.34	64.00			0.00	0.00	0.619	
2	470	8.875	8.28	63.48			0.00	0.00	0.6	
3	705	8.612	8.04	61.65			0.00	0.00	0.576	
4	940	8.224	7.64	58.63			0.00	0.00	0.581	
6	1410	7.217	6.66	51.11			0.00	0.00	0.554	
8	1880	6.303	5.76	44.19			0.00	0.00	0.542	
10	2350	5.517	4.99	38.25			0.00	0.00	0.531	
15	3525	4.267	3.76	28.83			0.00	0.00	0.507	
20	4700	3.457	2.95	22.71			0.00	0.00	0.496	
30	7050	2.397	1.93	14.77			0.00	0.00	0.472	
40	9400	1.868	1.40	10.76			0.00	0.00	0.466	
50	11750	1.619	1.16	8.90			0.00	0.00	0.458	

Relaxation measurements
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Material: Polysciences #19131 lot # : 82307
Descript.:0.047micron (s.d. 0.003) superparamag. particles/polystyrene matrix in 0.5% agar gel
Temp. : 37C Date: Feb. 7,89
[Fe]= 7.28 u-g/ml = 0.1304 mM

Frequency	Field	1/T1	1/T1 -1/T1 (agar)	R1	Comments	1/T2	1/T2 -1/T2 (agar)	R2	1/T1 (agar)	1/T2 (agar)
MHz	Gauss	1/s	1/s	1/(s*mM)		1/s	1/s	1/(s*mM)	1/s	1/s
0.02	4.7	8.807	6.45	49.45	Relaxometer # 35		0.00	0.00	2.357	
0.03	7.05	8.3	6.06	46.47			0.00	0.00	2.243	
0.04	9.4	7.765	5.60	42.97			0.00	0.00	2.163	
0.06	14.1	7.139	5.32	40.80			0.00	0.00	1.821	
0.08	18.9	6.463	4.88	37.42			0.00	0.00	1.595	
0.1	23.5	6.231	4.83	37.03			0.00	0.00	1.414	
0.15	35.25	5.738	4.64	35.58			0.00	0.00	1.1	
0.2	47	5.516	4.59	35.24			0.00	0.00	0.922	
0.3	70.5	5.417	4.68	35.37			0.00	0.00	0.741	
0.4	94	5.526	4.87	37.36			0.00	0.00	0.655	
0.6	141	5.807	5.24	40.19			0.00	0.00	0.563	
0.8	188	6.133	5.61	43.04			0.00	0.00	0.523	
1	235	6.471	5.98	45.87			0.00	0.00	0.492	
1.5	352.5	6.756	6.30	48.29			0.00	0.00	0.451	
2	470	6.986	6.55	50.22			0.00	0.00	0.439	
3	705	6.943	6.53	50.06			0.00	0.00	0.417	
4	940	6.634	6.23	47.77			0.00	0.00	0.407	
6	1410	6.081	5.69	43.67			0.00	0.00	0.388	
8	1880	5.508	5.13	39.37			0.00	0.00	0.376	
10	2350	4.951	4.58	35.16			0.00	0.00	0.369	
15	3525	3.968	3.61	27.65			0.00	0.00	0.362	
20	4700	3.199	2.85	21.85			0.00	0.00	0.35	
30	7050	2.36	2.03	15.55			0.00	0.00	0.333	
40	9400	1.843	1.51	11.61			0.00	0.00	0.33	
50	11750	1.504	1.19	9.07			0.00	0.00	0.326	

E 020

Relaxation measurements
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Material: Polysciences #18153   lot # : 75457
Descript.:1-2 micron superpara-mag. particles/polystyrene matrix in 0.5% agar gel
Temp. : 20C   Date: March 9 89
[Fe]=   145 ug/ml =   2.5924 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (agar) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (agar) 1/s	R2 1/(s*mM)	1/T1 (agar) 1/s	1/T2 (agar) 1/s
0.02	4.7	7.393	3.61	1.40	Relaxometer # 57		0.00	0.00	3.55	
0.03	7.05	6.534	3.40	1.31			0.00	0.00		
0.04	9.4	5.397	3.21	1.24			0.00	0.00	2.235	
0.06	14.1	5.241	3.09	1.19			0.00	0.00	2.15	
0.08	18.8	4.774	2.91	1.12			0.00	0.00	1.863	
0.1	23.5	4.495	2.91	1.12			0.00	0.00	1.582	
0.15	35.25	4.023	2.79	1.08			0.00	0.00	1.237	
0.2	47	3.83	2.73	1.05			0.00	0.00	1.105	
0.3	70.5	3.616	2.65	1.02			0.00	0.00	0.925	
0.4	94	3.45	2.59	1.00			0.00	0.00	0.86	
0.6	141	3.348	2.57	0.99			0.00	0.00	0.772	
0.8	188	3.213	2.45	0.95			0.00	0.00	0.73	
1	235	3.082	2.38	0.92			0.00	0.00	0.705	
1.5	352.5	2.925	2.35	0.90			0.00	0.00	0.619	
2	470	2.755	2.17	0.83			0.00	0.00	[illegible]	
3	705	2.565	1.97	0.77			0.00	0.00	0.576	
4	940	2.376	1.80	0.69			0.00	0.00	0.551	
6	1410	2.155	1.60	0.62			0.00	0.00	0.554	
8	1880	1.955	1.41	0.54			0.00	0.00	0.542	
10	2350	1.824	1.29	0.50			0.00	0.00	0.531	
15	3525	1.62	1.11	0.43			0.00	0.00	0.509	
20	4700	1.473	0.95	0.38			0.00	0.00	0.493	
30	7050	1.169	0.69	0.27			0.00	0.00	0.479	
40	9400	1.039	0.57	0.22			0.00	0.00	0.455	
50	11750	0.89	0.43	0.16			0.00	0.00	0.458	

f237

Relaxation measurements
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Material: Seradyn M1180/311   lot # : M1-180/20/311
Descript.:0.5-4 (1.30 avg.) micron superparamag. (22% Fe3O4) particles/polystyrene matrix in 0.5% agar gel
Temp. : 37C   Date: Feb. 23,89
[Fe]= 7.28 u-g/ml = 0.1304 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (agar) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (agar) 1/s	R2 1/(s*mM)	1/T1 (agar) 1/s	1/T2 (agar) 1/s
0.02	4.7	5.246	2.89	22.16	Relaxometer # 39		0.00	0.00	2.357	
0.03	7.05	4.557	2.32	17.77			0.00	0.00	2.242	
0.04	9.4	4.144	2.04	15.66			0.00	0.00	2.103	
0.06	14.1	3.404	1.58	12.14			0.00	0.00	1.821	
0.08	18.8	2.875	1.29	9.90			0.00	0.00	1.585	
0.1	23.5	2.544	1.14	8.75			0.00	0.00	1.404	
0.15	35.25	2.02	0.92	7.05			0.00	0.00	1.1	
0.2	47	1.77	0.85	6.51			0.00	0.00	0.922	
0.3	70.5	1.541	0.80	6.14			0.00	0.00	0.741	
0.4	94	1.44	0.78	6.01			0.00	0.00	0.656	
0.6	141	1.355	0.79	6.04			0.00	0.00	0.569	
0.8	188	1.303	0.79	6.02			0.00	0.00	0.523	
1	235	1.285	0.79	6.08			0.00	0.00	0.492	
1.5	352.5	1.201	0.74	5.68			0.00	0.00	0.461	
2	470	1.174	0.74	5.64			0.00	0.00	0.439	
3	705	1.109	0.69	5.31			0.00	0.00	0.417	
4	940	1.061	0.65	5.02			0.00	0.00	0.407	
6	1410	0.978	0.59	4.53			0.00	0.00	0.383	
8	1880	0.92	0.54	4.17			0.00	0.00	0.375	
10	2350	0.858	0.49	3.76			0.00	0.00	0.368	
15	3525	0.764	0.40	3.08			0.00	0.00	0.362	
20	4700	0.707	0.36	2.74			0.00	0.00	0.35	
30	7050	0.589	0.26	1.97			0.00	0.00	0.332	
40	9400	0.528	0.20	1.52			0.00	0.00	0.33	
50	11750	0.492	0.17	1.30			0.00	0.00	0.322	

F 820

Relaxation measurements
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Materials: Seradyn MI130/311   Lot # : MI-180/20/311
Descript.:0.5-4 (1.30 avg.) micron superparamag. (32% Fe3O4) particles/polystyrene matrix in 0.5% agar gel
Temp. : 20C   Date: March 9,89
[Fe]= 72.3 u-g/ml = 1.3036 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (agar) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (agar) 1/s	R2 1/(s*mM)	1/T1 (agar) 1/s	1/T2 (agar) 1/s
0.02	4.7	10.184	6.60	5.07	Relaxometer # 50		0.00	0.00	3.58	
0.03	7.05	10.131	6.95	5.33			0.00	0.00		
0.04	9.4	9.781	7.07	5.37			0.00	0.00	2.785	
0.06	14.1	9.431	7.28	5.59			0.00	0.00	2.15	
0.08	18.8	9.393	7.53	5.78			0.00	0.00	1.863	
0.1	23.5	9.251	7.67	5.89			0.00	0.00	1.583	
0.15	35.25	9.284	8.02	6.15			0.00	0.00	1.267	
0.2	47	9.282	8.18	6.27			0.00	0.00	1.105	
0.3	70.5	9.358	8.42	6.46			0.00	0.00	0.937	
0.4	94	9.402	8.54	6.55			0.00	0.00	0.86	
0.6	141	9.444	8.67	6.65			0.00	0.00	0.775	
0.8	188	9.449	8.72	6.69			0.00	0.00	0.73	
1	235	9.633	8.93	6.85			0.00	0.00	0.705	
1.05	246.75	9.553	8.86	6.79			0.00	0.00	0.695	
1.2	282	9.555	8.86	6.82			0.00	0.00		
1.4	329	9.495	8.86	6.80			0.00	0.00	0.652	
1.5	352.5	9.202	8.58	6.58			0.00	0.00	0.619	
2	470	9.156	8.56	6.56			0.00	0.00	0.6	
3	705	8.731	8.16	6.26			0.00	0.00	0.576	
4	940	8.484	7.90	6.06			0.00	0.00	0.581	
6	1410	7.648	7.09	5.44			0.00	0.00	0.554	
8	1880	7.103	6.57	5.04			0.00	0.00	0.543	
10	2350	6.731	6.20	4.76			0.00	0.00	0.531	
15	3525	5.643	5.13	3.94			0.00	0.00	0.509	
20	4700	5.193	4.70	3.60			0.00	0.00	0.495	
30	7050	3.842	3.37	2.59			0.00	0.00	0.472	
40	9400	3.197	2.73	2.10			0.00	0.00	0.455	
50	11750	2.748	2.28	1.75			0.00	0.00	0.435	

G 820

Relaxation measurements
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Materials: Seradyn MI180/335   Lot # : MI-180/20/335
Descript.:0.5-5 (1.70 u/g.) micron superparamag. (23.1% Fe3O4) particles:polystyrene matrix in 0.5% agar gel
Temp. : 20C   Date: March 9,89
[Fe]= 72.8 u-g/ml = 1.3035 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (agar) 1/s	R1 1/(sec*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (agar) 1/s	R2 1/(s*mM)	1/T1 (agar) 1/s	1/T2 (agar) 1/s
0.02	4.7	10.973	7.39	5.67	Relaxometer # 51		0.00	0.00	3.58	
0.03	7.05	10.746	7.56	5.80			0.00	0.00		
0.04	9.4	10.254	7.47	5.73			0.00	0.00	2.785	
0.06	14.1	9.749	7.60	5.83			0.00	0.00	2.15	
0.08	18.8	9.591	7.73	5.93			0.00	0.00	1.863	
0.1	23.5	9.371	7.78	5.97			0.00	0.00	1.593	
0.15	35.25	9.459	8.19	6.28			0.00	0.00	1.267	
0.2	47	9.245	8.14	6.24			0.00	0.00	1.105	
0.3	70.5	9.205	8.27	6.34			0.00	0.00	0.937	
0.4	94	9.066	8.21	6.30			0.00	0.00	0.86	
0.6	141	9.115	8.34	6.40			0.00	0.00	0.775	
0.8	188	8.852	8.13	6.24			0.00	0.00	0.73	
1	235	8.904	8.10	6.21			0.00	0.00	0.795	
1.5	352.5	8.423	7.80	5.99			0.00	0.00	0.619	
2	470	8.17	7.57	5.81			0.00	0.00	0.6	
3	705	7.605	7.03	5.39			0.00	0.00	0.575	
4	940	7.275	6.69	5.14			0.00	0.00	0.581	
6	1410	6.53	5.98	4.59			0.00	0.00	0.554	
8	1880	5.955	5.41	4.15			0.00	0.00	0.542	
10	2350	5.544	5.01	3.85			0.00	0.00	0.531	
15	3525	4.747	4.24	3.25			0.00	0.00	0.507	
20	4700	3.833	3.34	2.56			0.00	0.00	0.496	
30	7050	2.921	2.50	1.92			0.00	0.00	[illegible]	
40	9400	2.491	2.03	1.55			0.00	0.00	0.455	
50	11750	2.152	1.70	1.31			0.00	0.00	0.458	

H237

Relaxation measurements
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Material: Iron oxide   lot # : 82307
Descript.:Iron oxide prepared according to a method adapted from Sugimoto & Matjevic (j. of Colloid and Surface Science)
Temp. : 37C   Date: Feb. 16,87
[Fe]=   7.28 ug/ml =   0.1304 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (agar) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (agar) 1/s	R2 1/(s*mM)	1/T1 (agar) 1/s	1/T2 (agar) 1/s
0.02	4.7	5.029	2.67	20.50	Relaxometer # 3B		0.00	0.00	2.357	
0.03	7.05	4.308	2.07	15.85			0.00	0.00	2.242	
0.04	9.4	3.772	1.67	12.83			0.00	0.00	2.103	
0.06	14.1	2.934	1.16	8.92			0.00	0.00	1.821	
0.08	18.8	2.435	0.85	6.52			0.00	0.00	1.585	
0.1	23.5	2.085	0.69	5.22			0.00	0.00	1.404	
0.15	35.25	1.537	0.44	3.37			0.00	0.00	1.1	
0.2	47	1.267	0.34	2.65			0.00	0.00	0.922	
0.3	70.5	0.997	0.26	1.98			0.00	0.00	0.741	
0.4	94	0.869	0.21	1.63			0.00	0.00	0.655	
0.6	141	0.749	0.16	1.39			0.00	0.00	0.562	
0.8	188	0.695	0.17	1.32			0.00	0.00	0.523	
1	235	0.655	0.15	1.25			0.00	0.00	0.492	
1.5	352.5	0.61	0.15	1.14			0.00	0.00	0.451	
2	470	0.585	0.15	1.13			0.00	0.00	0.439	
3	705	0.55	0.13	1.02			0.00	0.00	0.417	
4	940	0.527	0.12	0.92			0.00	0.00	0.407	
6	1410	0.499	0.11	0.85			0.00	0.00	0.388	
8	1880	0.481	0.11	0.81			0.00	0.00	0.376	
10	2350	0.469	0.10	0.77			0.00	0.00	0.368	
15	3525	0.434	0.07	0.55			0.00	0.00	0.362	
20	4700	0.423	0.07	0.56			0.00	0.00	0.35	
30	7050	0.394	0.06	0.48			0.00	0.00	0.332	
40	9400	0.379	0.05	0.38			0.00	0.00	0.33	
50	11750	0.367	0.04	0.35			0.00	0.00	0.322	

K820

Relaxation measurements
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Material: Seradyn M1070/319   Lot # : M1-070/60/319
Descript.:0.5-4 (1.30 avg.) micron superparamag. (28% Fe3O4) particles/polystyrene matrix in 0.5% agar gel
Temp. : 20C   Date: March 9,89
[Fe]=   72.9 u-g/ml =   1.3035 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (agar) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (agar) 1/s	R2 1/(s*mM)	1/T1 (agar) 1/s	1/T2 (agar) 1/s
0.02	4.7	8.655	5.07	3.89	Relaxometer # 52		0.00	0.00	3.59	
0.03	7.05	8.563	5.33	4.13			0.00	0.00		
0.04	9.4	8.549	5.76	4.42			0.00	0.00	2.785	
0.06	14.1	8.639	6.49	4.98			0.00	0.00	2.15	
0.08	18.8	8.735	6.97	5.27			0.00	0.00	1.833	
0.1	23.5	8.725	7.14	5.48			0.00	0.00	1.589	
0.15	35.25	9.149	7.83	6.04			0.00	0.00	1.259	
0.2	47	9.311	8.21	6.30			0.00	0.00	1.101	
0.3	70.5	9.552	8.65	6.63			0.00	0.00	0.937	
0.4	94	9.69	8.83	6.77			0.00	0.00	0.85	
0.6	141	9.747	8.77	6.83			0.00	0.00	0.775	
0.8	188	9.338	8.65	6.64			0.00	0.00	0.73	
1	235	9.2	8.50	6.58			0.00	0.00	0.705	
1.5	352.5	8.451	7.83	6.01			0.00	0.00	0.619	
2	470	7.952	7.25	5.56			0.00	0.00	0.6	
3	705	6.909	6.33	4.85			0.00	0.00	0.576	
4	940	5.977	5.40	4.14			0.00	0.00	0.531	
6	1410	5.033	4.47	3.43			0.00	0.00	0.564	
8	1880	4.245	3.70	2.84			0.00	0.00	0.542	
10	2350	3.805	3.27	2.51			0.00	0.00	0.531	
15	3525	3.076	2.57	1.97			0.00	0.00	0.519	
20	4700	2.636	2.14	1.64			0.00	0.00	0.496	
30	7050	1.993	1.52	1.17			0.00	0.00	0.473	
40	9400	1.632	1.17	0.87			0.00	0.00	0.466	
50	11750	1.452	0.99	0.76			0.00	0.00	0.453	

L405

Relaxation measurements
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Material: Polysciences #19633   lot # : 86410
Descript.:Magnetite particles coated w/ polymer (magnetite/polymer = 2)
Temp. : 5C   Date: March 16,89
[Fe]=   2.17 u-g/ml =   0.0339 mM

Frequency	Field	1/T1	1/T1 -1/T1 (H2O)	R1	Comments	1/T2	1/T2 -1/T2 (H2O)	R2	1/T1 (H2O)	1/T2 (H2O)
MHz	Gauss	1/s	1/s	1/(s*mM)		1/s	1/s	1/(s*mM)	1/s	1/s
0.01	2.35	31.237	30.765	791.77	Relaxometer # 62		0	0.00	0.472	
0.02	4.7	29.843	29.371	755.89			0	0.00	0.472	
0.1	23.5	26.293	25.822	654.71			0	0.00	0.47	
0.5	117.5	22.719	22.256	572.78			0	0.00	0.453	
1	235	20.615	20.155	518.71			0	0.00	0.45	
1.5	352.5	18.356	18.403	473.75					0.456	
10	2350	7.337	6.954	178.97			0	[illegible]	0.433	
15	3525	5.303	4.9805	125.69						
50	11750	1.594	1.203	31.01			0	0.00	0.393	

L410

Relaxation measurements
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Material: Polysciences #19633   lot # : 86410
Descript.:Magnetite particles coated w/ polymer (magnetite/polymer = 2)
Temp. : 10C   Date: March 16,89
[Fe]=   2.17 u-g/ml = 0.0389 mM

Frequency Mhz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (H2O) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (H2O) 1/s	R2 1/(s*mM)	1/T1 (H2O) 1/s	1/T2 (H2O) 1/s
0.01	2.35	30.645	30.173	776.53	Relaxometer # 62		0	0.00	0.472	
0.02	4.7	29.5	29.023	747.05			0	0.00	0.472	
0.1	23.5	26.963	26.493	681.82			0	0.00	0.47	
0.5	117.5	23.145	22.682	583.74			0	0.00	0.463	
1	235	21.259	20.799	535.28			0	0.00	0.46	
1.5	352.5	19.697	19.231	494.93					0.456	
10	2350	7.518	7.085	182.34			0	0.00	0.433	
15	3525	5.452	5.0245	129.31						
50	11750	1.65	1.261	32.45			0	0.00	0.389	

L415

Relaxation measurements
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Material: Polysciences #19623   lot # : 86410
Descript.: Magnetite particles coated w/ polymer (magnetite/polymer = 2)
Temp. : 15C   Date: March 15,89
(Fe)= 2.17 u-g/ml = 0.0389 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (H2O) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (H2O) 1/s	R2 1/(s*mM)	1/T1 (H2O) 1/s	1/T2 (H2O) 1/s
0.01	2.35	30.454	29.932	771.62	Relaxometer # 62		0	0.00	0.472	
0.02	4.7	29.789	29.317	754.50			0	0.00	0.472	
0.1	23.5	26.528	26.058	670.63			0	0.00	0.47	
0.5	117.5	23.4	22.937	590.31			0	0.00	0.463	
1	235	21.809	21.349	549.44			0	0.00	0.46	
1.5	352.5	20.366	19.91	512.40					0.456	
10	2350	8.023	7.59	195.34			0	0.00	0.433	
15	3525	5.713	5.2855	136.03						
50	11750	1.674	1.285	33.07			0	0.00	0.389	

L420

Relaxation measurements

Material: Polysciences #19633   lot # : 36410
Description: Magnetite particles coated w/ polymer (magnetite/polymer = 2)
Temp. : 20C   Date: March 16,89
[Fe]=   2.17 ug/ml =   0.0389 mM

Frequency	Field	1/T1	1/T1 -1/T1 (H2O)	R1	Comments	1/T2	1/T2 -1/T2 (H2O)	R2	1/T1 (H2O)	1/T2 (H2O)
MHz	Gauss	1/s	1/s	1/(s*mM)		1/s	1/s	1/(s*mM)	1/s	1/s
0.01	2.35	29.701	29.229	757.33	Relaxometer # 62		0	0.00	0.472	
0.02	4.7	29.039	28.567	735.63			0	0.00	0.472	
0.1	23.5	22.535	22.065	570.67			0	0.00	.47	
0.5	117.5	23.53	23.057	593.35			0	0.00	0.463	
1	235	22.121	21.651	557.47			0	0.00	0.45	
1.5	352.5	20.527	20.071	516.55					0.455	
10	2350	7.977	7.544	194.15			0	0.00	0.433	
15	3525	5.593	5.2555	135.25						
50	11750	1.709	1.319	33.95			0	0.00	0.389	

L 425

Relaxation measurements
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Material: Polysciences #19633   lot # : B6410
Descript.:Magnetite particles coated w/ polymer (magnetite/polymer = 2)
Temp. : 25C   Date: March 16,89
[Fe]=   2.17 u-g/ml =   0.0389 mM

Frequency	Field	1/T1	1/T1 -1/T1 (H2O)	R1	Comments	1/T2	1/T2 -1/T2 (H2O)	R2	1/T1 (H2O)	1/T2 (H2O)
MHz	Gauss	1/s	1/s	1/(s*mM)		1/s	1/s	1/(s*mM)	1/s	1/s
0.01	2.35	29.643	29.171	750.74	Relaxometer # 62		0	0.00	0.472	
0.02	4.7	28.445	27.973	719.91			0	0.00	0.472	
0.1	23.5	25.892	25.422	654.26			0	0.00	0.47	
0.5	117.5	23.167	22.704	584.31			0	0.00	0.463	
1	235	22.394	21.924	564.23			0	0.00	0.45	
1.5	352.5	20.692	20.236	520.79					0.456	
10	2350	8.291	7.859	202.23			0	0.00	0.433	
15	3525	5.912	5.4945	141.15						
50	11750	1.723	1.334	34.33			0	0.00	0.389	

L430

Relaxation measurements
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Material: Polysciences #19633 lot # : 86410
Descript.:Magnetite particles coated w/ polymer (magnetite/polymer = 2)
Temp. : 30C Date: March 16,89
[Fe]= 2.17 ug/ml = 0.0389 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (H2O) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (H2O) 1/s	R2 1/(s*mM)	1/T1 (H2O) 1/s	1/T2 (H2O) 1/s
0.01	2.35	28.223	27.751	714.20	Relaxometer # 62		0	0.00	0.472	
0.02	4.7	27.44	26.968	694.05			0	0.00	0.472	
0.1	23.5	25.156	24.685	635.32			0	0.00	0.47	
0.5	117.5	22.978	22.515	579.44			0	0.00	0.463	
1	235	21.929	21.467	552.52			0	0.00	0.46	
1.5	352.5	20.755	20.299	522.41					0.455	
10	2350	8.249	7.816	201.15			0	0.00	0.432	
15	3525	6.097	5.6695	145.91						
50	11750	1.773	1.364	35.62			0	0.00	0.389	

L 435

Relaxation measurements
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Material: Polysciences #19633   lot # : 86410
Descript.:Magnetite particles coated w/ polymer (magnetite/polymer = 2)
Temp. : 35C   Date: March 16,89
(Fe)=   2.17 u-g/ml =   0.0389 mM

Frequency MHz	Field Gauss	1/T1 1/s	1/T1 -1/T1 (H2O) 1/s	R1 1/(s*mM)	Comments	1/T2 1/s	1/T2 -1/T2 (H2O) 1/s	R2 1/(s*mM)	1/T1 (H2O) 1/s	1/T2 (H2O) 1/s
0.01	2.35	26.943	26.471	681.36	Relaxometer # 62		0	0.00	0.472	
0.02	4.7	26.621	26.149	672.97			0	0.00	0.472	
0.1	23.5	24.113	23.645	609.53			0	0.00	0.47	
0.5	117.5	22.666	22.203	571.42			0	0.00	0.453	
1	235	21.978	21.518	553.79			0	0.00	0.46	
1.5	352.5	20.553	20.097	517.22					0.452	
10	2350	8.217	7.784	200.33			0	0.00	0.433	
15	3525	6.143	5.7155	147.09						
50	11750	1.802	1.413	36.36			0	0.00	0.389	

520

Relaxation measurements
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Materials Polysciences #19533   lot # : 85410
Descript.:Magnetite particles coated w/ polymer (magnetite/polymer = 2)
Temp. : 20C   Date: March 10,89
(Fe)=   0.728 u-g/ml =   0.0130 mM

Frequency	Field	1/T1	1/T1 -1/T1 (H2O)	R1	Comments	1/T2	1/T2 -1/T2 (H2O)	R2	1/T1 H2O	1/T2 H2O
MHz	Gauss	1/s	1/s	1/(s*mM)		1/s	1/s	1/(s*mM)	1/s	1/s
0.01	2.35	10.404	9.932	761.91	Relaxometer #36		0	0.00	0.472	
0.015	3.525	10.263	9.79	751.05			0	0.00	0.473	
0.017	3.995	10.252	9.79	751.02			0	0.00	0.473	
0.02	4.7	10.092	9.62	737.98			0	0.00	0.473	
0.025	5.875	10.042	9.5705	734.16						
0.03	7.05	9.67	9.199	705.69			0	0.00	0.471	
0.05	11.75	9.407	8.936	685.51			0	0.00	0.471	
0.1	23.5	9.092	8.622	661.42			0	0.00	0.47	
0.13	30.55	8.97	8.503	652.29			0	0.00		
0.15	35.25	8.982	8.517	653.36			0	0.00	0.465	
0.2	47	8.654	8.189	628.97			0	0.00	0.465	
0.23	54.05	8.58	8.117	622.66			0	0.00	0.463	
0.25	58.75	8.356	7.893	605.50			0	0.00		
0.3	70.5	8.372	7.909	606.72			0	0.00	0.463	
0.4	94	8.156	7.693	590.15			0	0.00	0.463	
0.6	141	7.921	7.459	572.20			0	0.00		
1	235	7.627	7.167	549.80			0	0.00	0.46	
1.5	352.5	7.067	6.611	507.15					0.456	
2	470	6.567	6.115	469.10						
3	705	5.609	5.165	396.22			0	0.00	0.444	
4	940	4.963	4.5215	346.86						
5	1175	4.371	3.932	301.64					0.439	
6	1410	4.07	3.634	278.77						
7	1645	3.673	3.24	248.55			0	0.00	0.433	
7.5	1762.5	3.533	3.1	237.81						
10	2350	2.872	2.439	187.10			0	0.00	0.433	
15	3525	2.163	1.7395	133.44						
20	4700	1.724	1.31	100.49			0	0.00	0.414	
30	7050	1.215	0.814	62.44			0	0.00	0.401	
40	9400	0.959	0.574	44.03			0	0.00	0.394	
50	11750	0.819	0.43	32.99			0	0.00	0.389	